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EFFECT OF VARIANCES AND MANUFACTURING TOLERANCES ON THE DESIGN STRENGTH AND LIFE OF MECHANICALLY FASTENED COMPOSITE JOINTS

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The objective of this program is development of failure criterion and improved fatigue life prediction methodology of mechanically fastened joints in advanced composite structure. This report summarizes activity for the period 15 February 1978 to 30 June 1978.

Program activities are divided into five tasks:

Task 1 - Literature Survey

Task 2 - Evaluation of Joint Design Variables

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20. Abstract (Continued)

Task 3 - Evaluation of Manufacturing and Service Anomalies
Task 4 - Evaluation of the Effect of Critical Joint Design Parameters on Fatigue Life
Task 5 - Development of Final Analyses and Correlation

This report documents Task 1 - Literature Survey activities. Summarized are the state-of-the-art in design and analysis of mechanically fastened composite joints, selected methodology, conclusions, and recommendations for the remainder of this program.

FOREWORD

The work reported herein was performed by the McDonnell Aircraft Company (MCAIR) of the McDonnell-Douglas Corporation (MDC), St. Louis, Missouri, under Air Force Contract F33615-77-C-3140, for the Air Force Flight Dynamics Laboratory (AFFDL) at Wright-Patterson Air Force Base, Ohio. This effort was conducted under Task 1 of Project No. 2401 "Structural Mechanics", Task 240101 "Structural Integrity for Military Aerospace Vehicles", Work Unit 24010110 "Effect of Variances and Manufacturing Tolerances on the Design Strength and Life of Mechanically Fastened Composite Joints." Roger J. Aschenbrenner (AFFDL/FBE) was the Air Force Project Engineer. The work described was conducted during the period 15 February 1978 through 31 June 1978.

Program manager was Mr. Joseph F. Schier, Chief Technology Engineer, MCAIR Structural Research Department. Principal investigator was Mr. Samuel P. Garbo, MCAIR Structural Research Department.

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INTRODUCTION

One of the major advantages of advanced composite structures over conventional metal structures is a significant reduction in the number of parts and joints required, but there will always be areas where joints and attachments will be necessary in the assembly of major structural components. Eliminating structural joints is impractical in present-day aircraft because of the requirements for inspection, manufacturing breaks, assembly and equipment access, and replacement of damaged structures.

Design policies for joining metal elements are based on years of experience with isotropic and homogeneous materials. Optimum joint proportions have evolved from essentially invariant relationships between tension, shear, and bearing strengths of structural metals. Because of the fundamental differences in properties caused by the anisotropy and nonhomogeneity of composites, manufacturing practices and design policies that were evolved for metal joints cannot be applied directly to composites. The basic strength and modulus relationships on which metal joint technology is based are variables in the composite structural design process. Advanced composites have practically none of the forgiving capabilities of the conventional yielding metals to redistribute loads and minimize stress concentrations. These materials also exhibit distinct failure modes which depend markedly on joint geometry, fastener patterns, material, layup, etc.

Reliable analytical procedures are needed for predicting failure and fatigue life of mechanically fastened composite joints. Currently, the strength of laminates mechanically fastened to substructure is generally determined experimentally for each specific layup because of a lack of failure analysis procedures to accurately account for the effects on joint strength of manufacturing tolerances and design variables. Development of this methodology

will result in reduced experimental costs, less conservatism in manufacturing and design tolerances, and lower component production costs without compromising reliability of the bolted composite joints.

Therefore, the overall objective of this program is development of failure criterion and improved fatigue life prediction methodology of mechanically fastened joints in advanced composite structure. Program activities are divided into five tasks:

Task 1 - Literature Survey

Task 2 - Evaluation of Joint Design Variables

Task 3 - Evaluation of Manufacturing and Service Anomalies

Task 4 - Evaluate the Effect of Critical Joint Design Parameters on Fatigue Life

Task 5 - Development of Final Analysis and Correlation

The program schedule for all tasks is summarized in Figure 1. This report documents Task 1 - Literature Survey activities.

The objective in Task 1 was to assess the state-of-the-art in mechanically fastened joints in advanced composite structure. This required a literature survey of previous and on-going work related to design and analysis methodology.

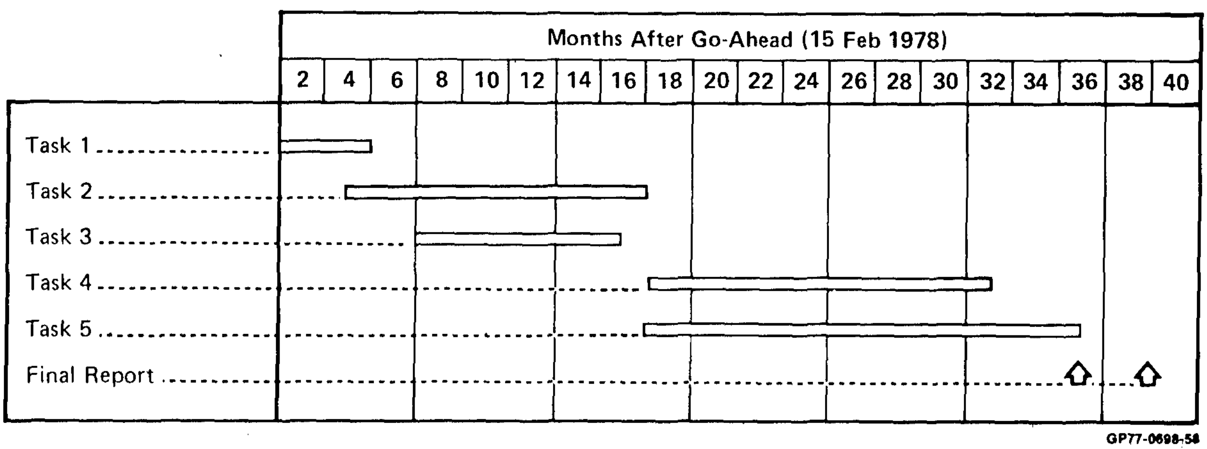

FIGURE 1
PROGRAM SCHEDULE - BOLTED COMPOSITE JOINTS

SECTION II
SUMMARY

This report summarizes the state-of-the-art in design and analysis of mechanically fastened composite joints, and methodology selected for improvement in the remainder of this Air Force funded program.

Design and analysis of bolted composite joints in aircraft structural components follows similar directions throughout the industry (Figure 2). Analysis proceeds from overall structural analysis, to localized joint idealization and bolt-load distribution analysis, to assessment of strength through utilization of joint failure criteria at individual fastener holes. Certain aspects of bolted composite joint analysis can be considered conventional. This includes determination of overall structural internal load distributions, one-dimensional joint idealization and joint bolt-load distributions. Detailed stress analysis performed at individual fastener holes and associated application of joint failure criteria are not conventional and represent a needed area of research activity.

Physical variables considered relevant for accurate solutions were generally agreed upon throughout the industry (e.g. composite material strength and stiffness anisotropy, finite width effects, biaxial in-plane load effects, arbitrary fastener load direction, non-linear or inelastic effect at the fastener hole boundary). However, major differences occurred in the degree to which these variables were accounted for in particular analysis methods. Generally, while some investigators accounted for composite material anisotropy, effects of finite width were neglected. Some methods accounted for anisotropy and finite width but were not generalized to account for biaxial in-plane loadings and arbitrary fastener load directions. Other methods did not account for the very important non-linear or inelastic material effects which occur at the fastener hole boundary. A fundamental goal of this contracted research activity will

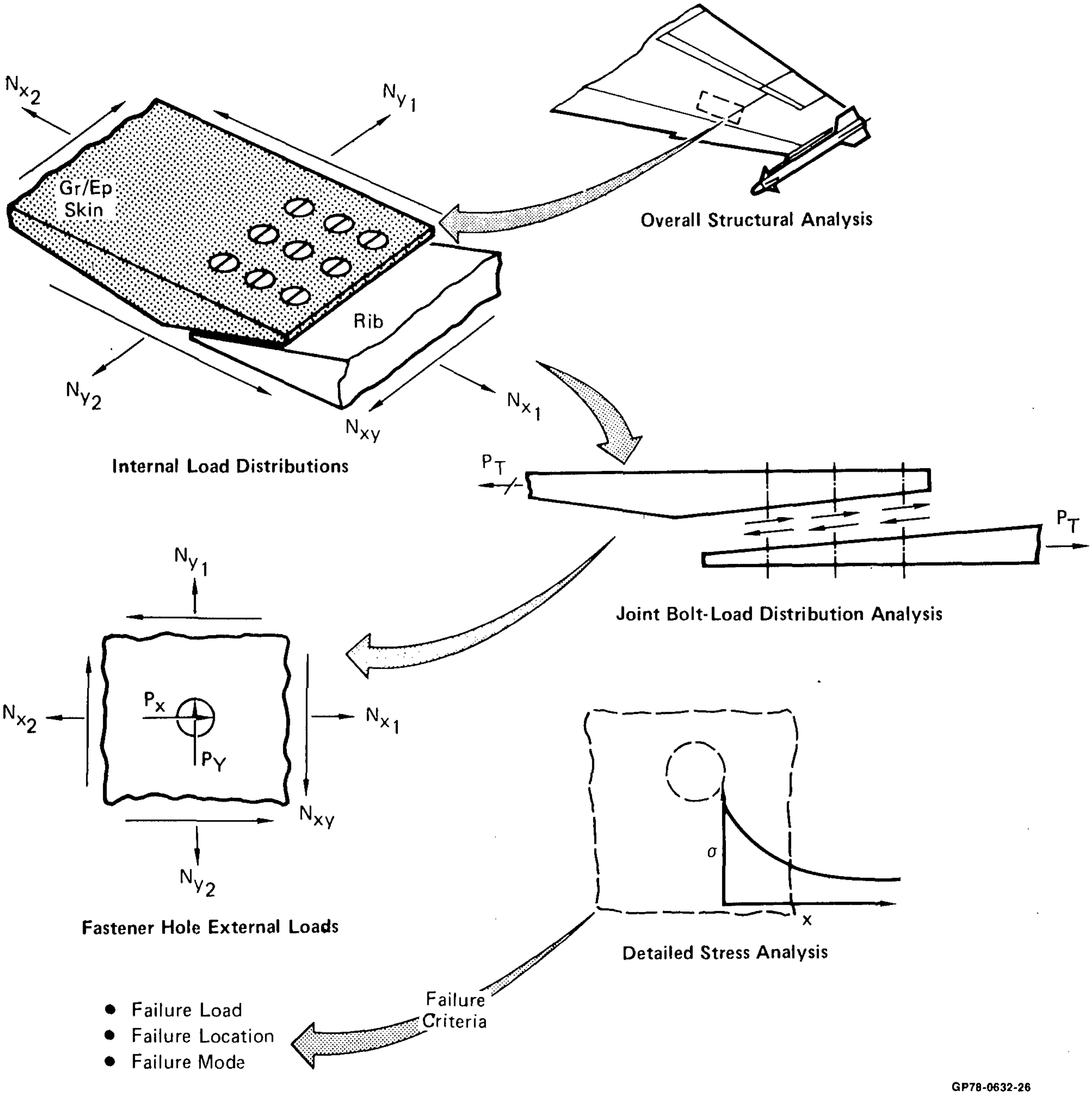

FIGURE 2

JOINT FAILURE ANALYSIS

be to combine the best analytic features contained in these existing static strength methodologies into one user-oriented general analysis procedure.

Fatigue of bolted composite joints is accounted for through an iterative design-test procedure. Bolted composite joints generally have a high fatigue life; consequently, most composite structural joints are designed for static strength only. Fatigue analysis methodology includes: (1) empirical correlations, (2) cumulative damage models, and (3) fracture mechanics models. Few methods have had extensive experimental verification. Government funded research on composite fatigue is continuing throughout the industry (reference Section III, 5).

For the remainder of this contract effort, failure prediction and improved fatigue life methodology will be developed for mechanically fastened joints in composite materials. The approach will be to conduct an experimental program, guided from a sound theoretical basis and to use the best available analytic methods. Correlation with generated test data will then be used to improve analytical methods.

SECTION III
MECHANICALLY FASTENED COMPOSITE JOINTS

In this section, an assessment is made of previous and continuing work involving mechanically fastened joints in advanced composite structure. Emphasis is placed on identification of commonly used types of bolted composite joints, common design practices in structural flight components, and assessment of current analytical techniques for prediction of joint load distributions, joint failure, and fatigue life.

1. COMMONLY USED TYPES OF JOINTS

Major aerospace composite structural components which were reviewed in the Task 1 - Literature Survey are listed in Figure 3. Aircraft reviewed ranged from a lightweight fighter aircraft (F-18) to the space shuttle. For these vehicles, composite structural components have been proposed or are currently in production on the fuselage, wing, and empennage, including both aerodynamic surface skins and substructure. All vehicles have mechanically fastened composite-to-composite or composite-to-metal joints. With the exception of modifications to the composite constituent plies (e.g., inserts or softening strips), mechanical joints were found to be configured much like those seen in conventional metal structure.

Three aircraft listed in Figure 3, the F-18 Hornet lightweight fighter, the AV-8B Harrier V/STOL tactical strike aircraft, and the B-1 bomber aircraft represent the latest state-of-the-art in production and research composite applications. Mechanically fastened joints in these aircraft are representative of all joint configurations found in any current or near term aircraft composite design component. The F-18 contains many composite-to-metal joints, the AV-8B has many composite-to-composite and to-metal designs, and the B-1 uses hybrid laminates and softening strips in composite-to-composite joints.

Aircraft	Composite Component	Application Status		Reference
		Research	Production	
F-18	Wing Skins (Inner and Outer)		X	McDonnell Douglas [1]
	Horizontal Stabilizer		X	McDonnell Douglas [1]
	Vertical Stabilizer		X	McDonnell Douglas [1]
	Speedbrake		X	McDonnell Douglas [1]
AV-8B	Wing Skins and Substructure	X	X	McDonnell Douglas [1]
B-1	Vertical Stabilizer	X		Rockwell
	Horizontal Stabilizer	X		Grumman
A-7D	Outer Wing Skin	X		Vought
	Wing Substructure	X		Vought
F-15	Speedbrake	X	X	McDonnell Douglas [1]
	Wing Skins and Substructure	X		McDonnell Douglas [1]
DC-10	Rudder	X		McDonnell Douglas [2]
L1011	Vertical Fin	X		Lockheed
Shuttle Orbiter	Aft Propulsion System		X	McDonnell Douglas [3]
	Payload Bay Doors		X	Rockwell
XFV-12A	Wing and Substructure	X		Rockwell
F-16	Wing Skins and Substructure	X		General Dynamics
	Vertical Stabilizer	X	X	General Dynamics

[1] McDonnell Aircraft Company

[2] Douglas Aircraft Company

[3] McDonnell Douglas Astronautics Company-East

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FIGURE 3
BOLTED JOINT EXPERIENCE IN AIRCRAFT COMPOSITE STRUCTURE APPLICATIONS

Approximately 10 percent of the F-18 Hornet structural weight is in graphite-epoxy tape materials. Mechanical fasteners attach conventional metal substructure to wing cover skins, empennage surfaces, control surfaces, speedbrake and numerous fuselage structural doors. Representative mechanical joint types and their locations are illustrated in Figure 4.

On the AV-8B Harrier, monolithic wing skins, sine wave stiffened spars and ribs, fairings, and control surfaces are fabricated from graphite-epoxy fabric or tape. Metal is used only for fasteners, local fittings and reinforcements. Composites account for approximately 20 percent of the total AV-8B structural weight. Representative mechanical joint types and their location are illustrated in Figure 5.

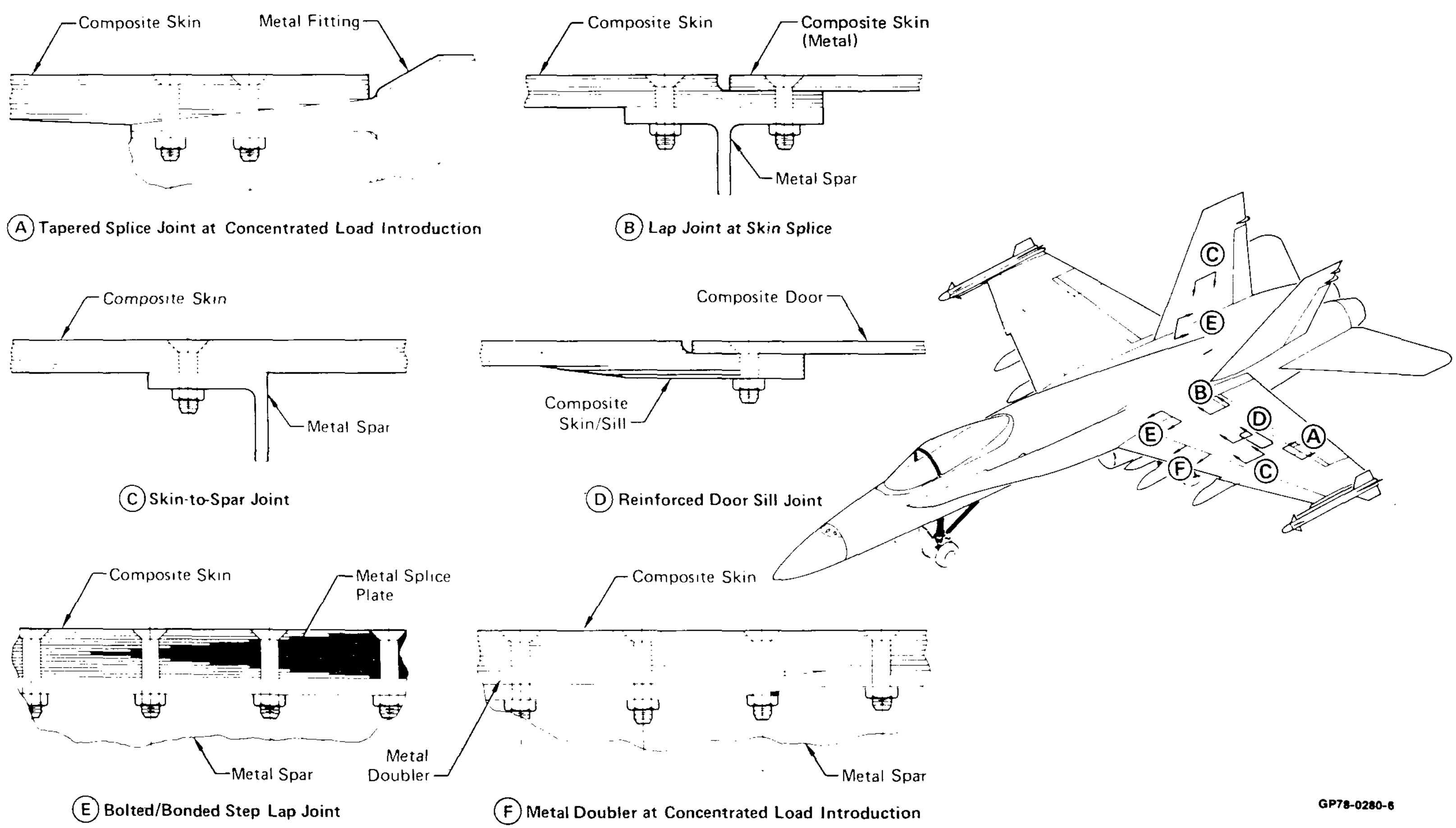

FIGURE 4
BOLTED COMPOSITE JOINTS ON F-18

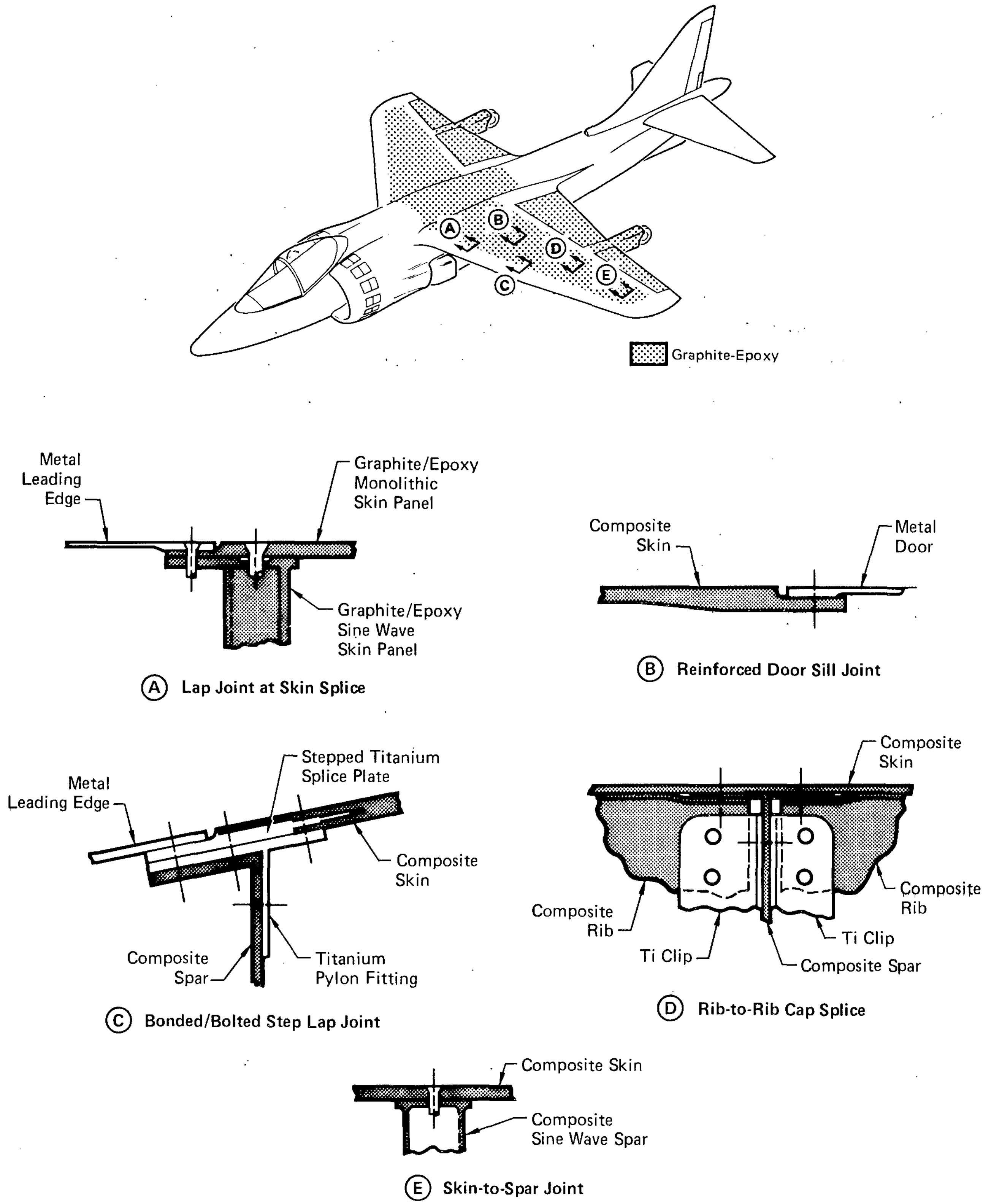

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FIGURE 5
AV-8B HARRIER BOLTED COMPOSITE JOINTS

Several B-1 components were studied under Air Force advanced development contracts (References 1, 2, and 3) for the application of advanced composite materials to this weapon system. These components included primary structure (vertical and horizontal stabilizer) and secondary structure (slat, flaps, and avionics bay door). Empennage components consisted of monolithic composite skins mechanically fastened to composite sine-wave spar substructure. Emphasis was placed on structural optimization through hybridization of composite material systems in both the basic monolithic cover areas for increased stiffness efficiency, and at mechanical fastener locations to reduce stress concentrations. Types of mechanical joints and their locations are illustrated in Figure 6.

a. Modeling and Characterization

Although joint types may be complex in appearance, each can be generically modeled as simple single- or double-lap specimen. As in metal structure, each mechanically fastened joint is characterized for analysis or testing by: (1) percent of load transferred at individual fasteners, (2) direction of fastener load relative to edge of parts, (3) load eccentricity, and (4) fastener types. However, in bolted composite joints special analytic considerations are required because of material stiffness and strength anisotropy and material nonhomogeneity.

Percent of load transferred interacts with degree of orthotropy (lay-up) to control the magnitude of stress concentrations which occur at any fastener hole. Additional interaction occurs with composite strength orthotropy. In joint configurations used in primary structure, percent of load transferred ranges from unloaded fastener holes possessing only by-pass stresses to highly loaded fastener holes where all load is transferred at a single fastener. Between these two limits, all values can and do occur, influencing joint failure mode, design, and laminate construction.

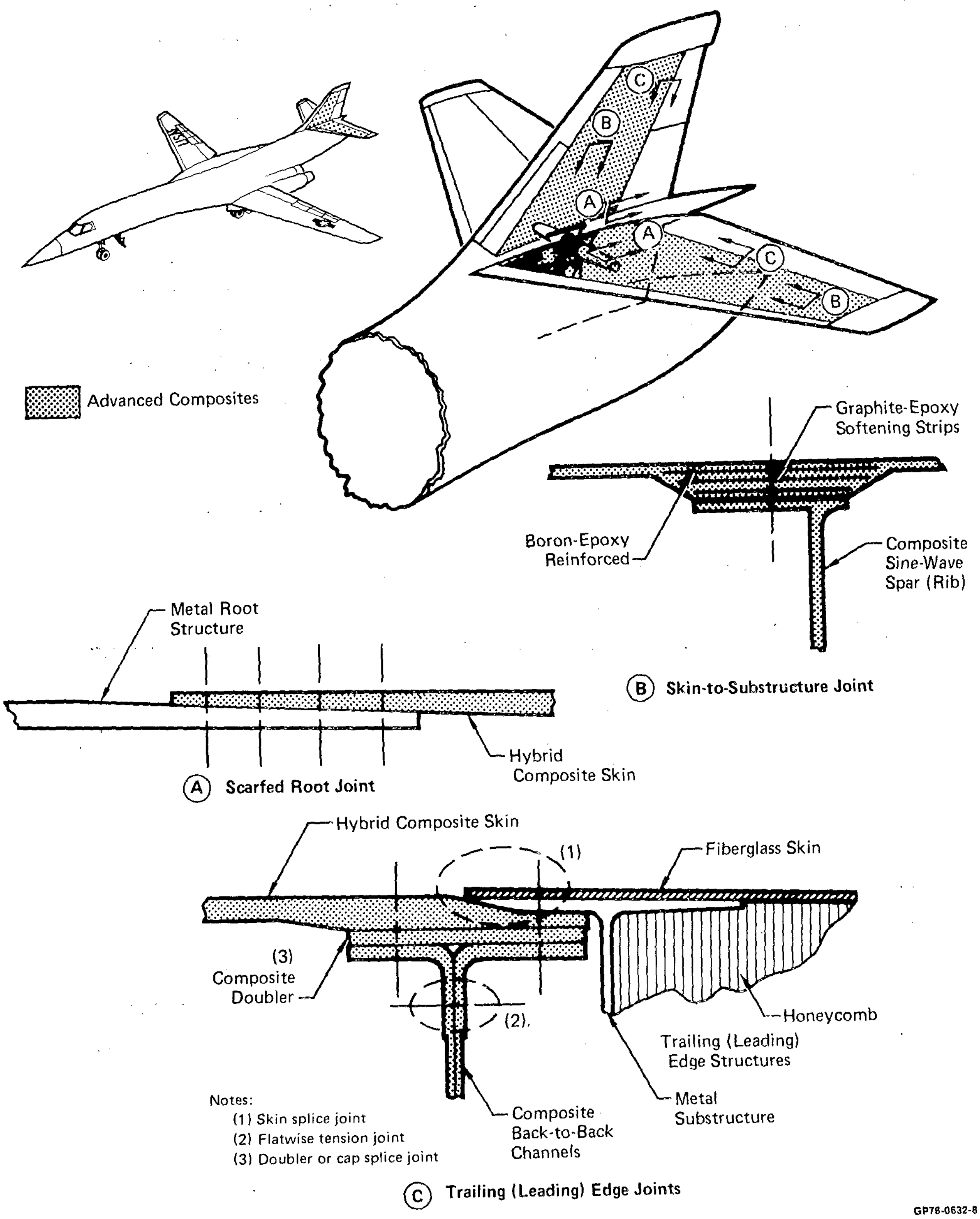

FIGURE 6
BOLTED COMPOSITE JOINTS ON B-1 EMPENNAGE (R&D)

Direction of fastener loads varied from being normal to the edge of the skin in the case of a chordwise wing skin splice, to parallel to skin edges such as in skin-to-spar joints. Loading normal to the skin edge introduces the possibility of failure modes (e.g. shear-out and tension cleavage failure modes) related to edge distance-to-diameter ratios generally not found in loading parallel to skin edges. This interaction of load direction and geometry is relevant to metal as well as composite joint members. In composite joint members, however, peak stresses at the fastener hole are affected by interactions between fastener load direction and material stiffness and strength anisotropy. This interaction of load direction and material anisotropy directly influences location and magnitude of peak stress concentrations and thus ultimately the composite member failure mode.

In Figures 4 through 6, examples of joint members loaded in single, double, or multiple shear planes are evident. Eccentricities produce variations in overall joint load distribution as well as in through-the-thickness stress distributions. These variations affect bolted composite joint failure load and mode because of interactions with material nonhomogeneity (ply stacking sequence) and strength anisotropy.

Fastener types play an important role because of through-the-thickness variations in bearing stress distribution related to load eccentricity. Both protruding head and countersunk head fasteners are used in composite joints. Design allowables, empirically determined, account for head fixity, and countersink depth-to-thickness effects.

Final joint designs are determined by an interactive design-analysis cycle accounting for load intensities, material system limitations, aerodynamic surface requirements, inspection and serviceability requirements, environmental considerations, weight savings, manufacturing requirements, and structural component geometric constraints.

2. COMMON DESIGN PRACTICES

In this survey, documents relating to aircraft or aircraft components (production parts as well as research efforts) were reviewed (Figure 7) for specific bolted composite joint design practices.

Application	Contractor	Reference
F-18	McDonnell Aircraft	4
AV-8B	McDonnell Aircraft	7
F-15	McDonnell Aircraft	8
B-1 Horizontal Stabilizer	Grumman	5
B-1 Vertical Stabilizer	Rockwell (LA)	1
F-16 Wing	General Dynamics	6
AV-7D Wing	Vought (LTV)	9

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FIGURE 7
LITERATURE SURVEY OF DESIGN PRACTICES

Design practices with respect to edge distance and fastener spacing in mechanically fastened joints are not clearly defined among the aircraft companies. Minimum allowed edge distance ranged from two-to-three times fastener diameters. Minimum allowed fastener spacing ranged from three-to-four diameters. These restrictions are linked to composite material design allowables established by experiments which reflect application requirements. Failure modes in loaded hole composites are related to interactions between laminate configuration and geometry. Thus, edge and pitch distance requirements reflect experimental data bases.

General agreement exists on fastener types and material combinations. Most companies (References 1, 4, 5, 6) recognized a potential corrosion problem exists between graphite-epoxy and various metals. Common practice is to prohibit direct contact between graphite-epoxy and aluminum, aluminum coated materials, cadmium plated steel, and monel steel in either fasteners or attaching structural members. Contact between these metals and graphite could result in corrosion

of the metal. Combinations of graphite-epoxy and stainless steel are acceptable if corrosion protection is provided such as wet sealant. Combinations of graphite-epoxy and titanium were universally accepted without requiring corrosion protection.

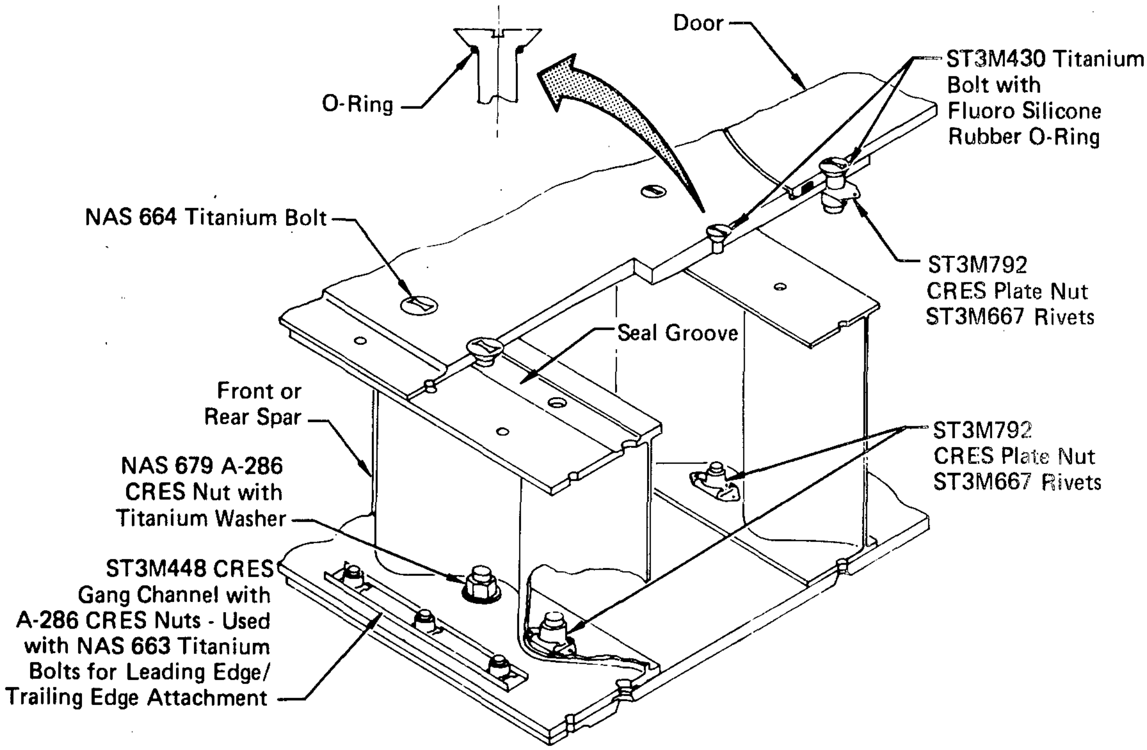
Generally, only tension head fasteners are used, no fasteners are installed in interference fit holes, no hole filling fasteners are permitted, and no vibration driving is done. Typically, clearance holes are produced in composites with a total diametric tolerance of .002-.004 inch. Such holes can be consistently produced by using special hole preparation techniques and tools (Reference 3). For flush fasteners in composites, countersink depths are limited to avoid "knife edge" bearing surfaces. Tension-head flush fasteners are used since shear-head flush fasteners cause local bearing damage due to their smaller head size which "roll-over", pulling through composite laminates. Torque values in composite structure were found to be consistent with conventional metal structure guidelines for fasteners primarily loaded in shear.

Joint details on the AV-8B (Reference 7) are illustrated in Figure 8. This figure shows typical configurations, fuel sealing configurations, and fastener types which this literature survey revealed are representative of industry-wide design practices.

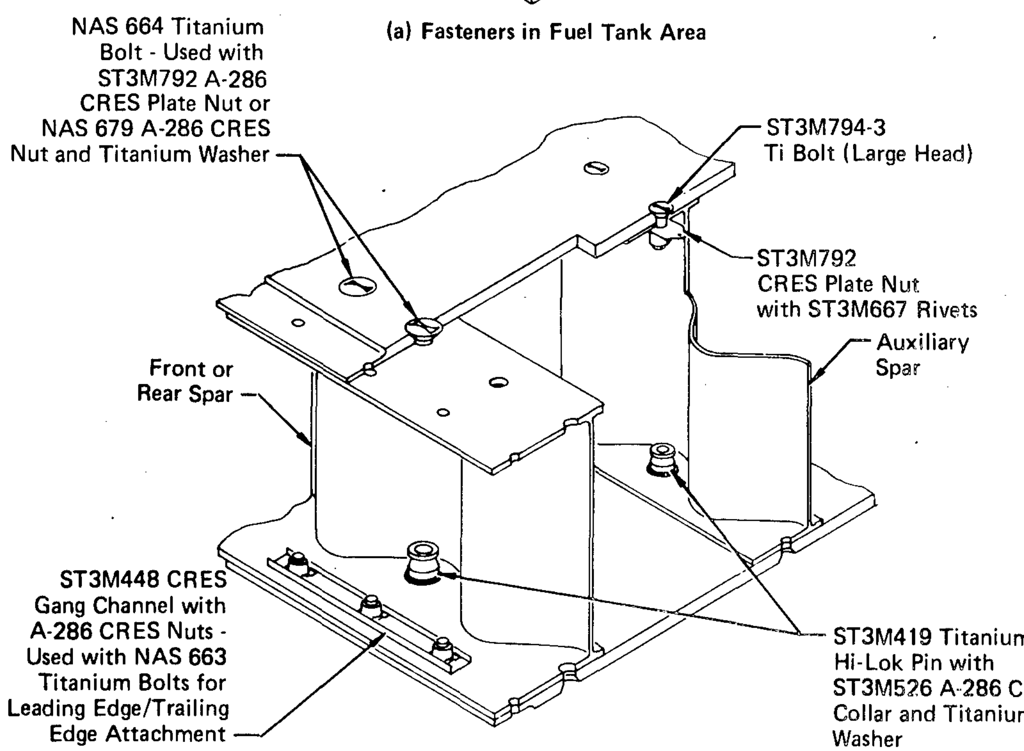
Aircraft companies (References 4, 5, 6) are working with fastener manufacturers to develop an improved blind fastener for composites. In some cases, blind fasteners create excessive clamp-up loads during installation and cause damage to the composite structure under the blind head.

3. LOAD DISTRIBUTION ANALYSIS

Overall analysis of a structural component is performed to determine internal load distributions in the vicinity of structural details requiring further analysis. Analysis is then performed to determine individual fastener loads and bypass-loads acting at each fastener hole. Finally, a



(a) Fasteners in Fuel Tank Area



(b) Fasteners in Dry Area

FIGURE 8 [redacted]

COMPOSITE APPLICATIONS WITH MECHANICAL FASTENERS

detailed analysis is performed to determine stress distributions in the composite material near the bolt. Having this final distribution of stresses, joint strength can be assessed by applying material failure criteria.

a. Analysis of Structural Components

Bolted joint load distribution analysis begins with determination of joint external loads. These applied loads are determined from overall structural analysis in which gross element stiffnesses are accounted for in solving redundant internal load distributions. Realistic engineering assumptions are required to reduce the complexity of the real structure to a tractable level for analysis. Typically where joints are present, the flexibility of fasteners is ignored because contributions of bolts and local joint structure to overall structural deformation is quite small.

A typical example of overall structural component analysis would be finite element modeling used to determine internal load distributions. Finite element idealizations of aircraft structural components quickly reach an economic limitation when geometric and material property variables alone are considered and individual fasteners and associated flexibilities are generally not included. An exception is noted in Reference 10 where flexibilities of fasteners were modeled in the local root area of the overall finite element model of the B-1 horizontal stabilizer. Locally within a model a single finite element may represent an area which in the actual structure would contain more than a single fastener. In most cases, there would be insufficient elements locally surrounding the modeled bolt to permit development of the very localized joint stress distributions. In essence, the component finite element model would be insensitive to bolt flexibilities unless a considerable increase in the number of elements accompanied each modeled fastener.

b. Joint Bolt-Load Distribution Analysis

Overall structural analysis provides external loads which act on joints. Engineering assumptions are made to represent multi-row and multi-column joints as one-column of in-line bolts. A good example of such assumptions is given by Gehring and Maines (Reference 11) for a horizontal stabilizer root-splice joint. The idealization assumptions, prior to joint bolt-load distribution analysis, are very important because they affect the degree of conservatism present in final margins of safety calculated at individual fastener holes. A representative idealization of a scarfed wingfold splice joint is shown in Figure 9. After external loads are obtained, conventional methods of analysis which determine load distributions at individual fastener shear faces are utilized.

Available methods have been surveyed in References 11, 12, and 13. These one-dimensional methods include analytic closed-form procedures for simple lap-joint configurations, and numerical procedures capable of handling more complex geometries and joints with multiple shear faces. Important variables such as plate and fastener stiffness properties, fastener clearance, material inelastic behavior, and joint eccentricities are included.

The contribution of each fastener to joint flexibility is dependent upon fastener stiffness, joint member stiffness, and load eccentricity, and must be accounted for to accurately determine individual fastener loads. For analysis, joint flexibilities are obtained experimentally from single fastener joint specimens. In metals, this type of data is available (Reference 14) for a wide variety of fasteners, sheet materials and thicknesses. In composites, however, this data is not as prevalent. Additionally, the anisotropy of composite material mechanical properties and laminate tailorability increases the test data which would be required to define all possible conditions. Consequently, data is usually generated on a "need" basis, inferred from

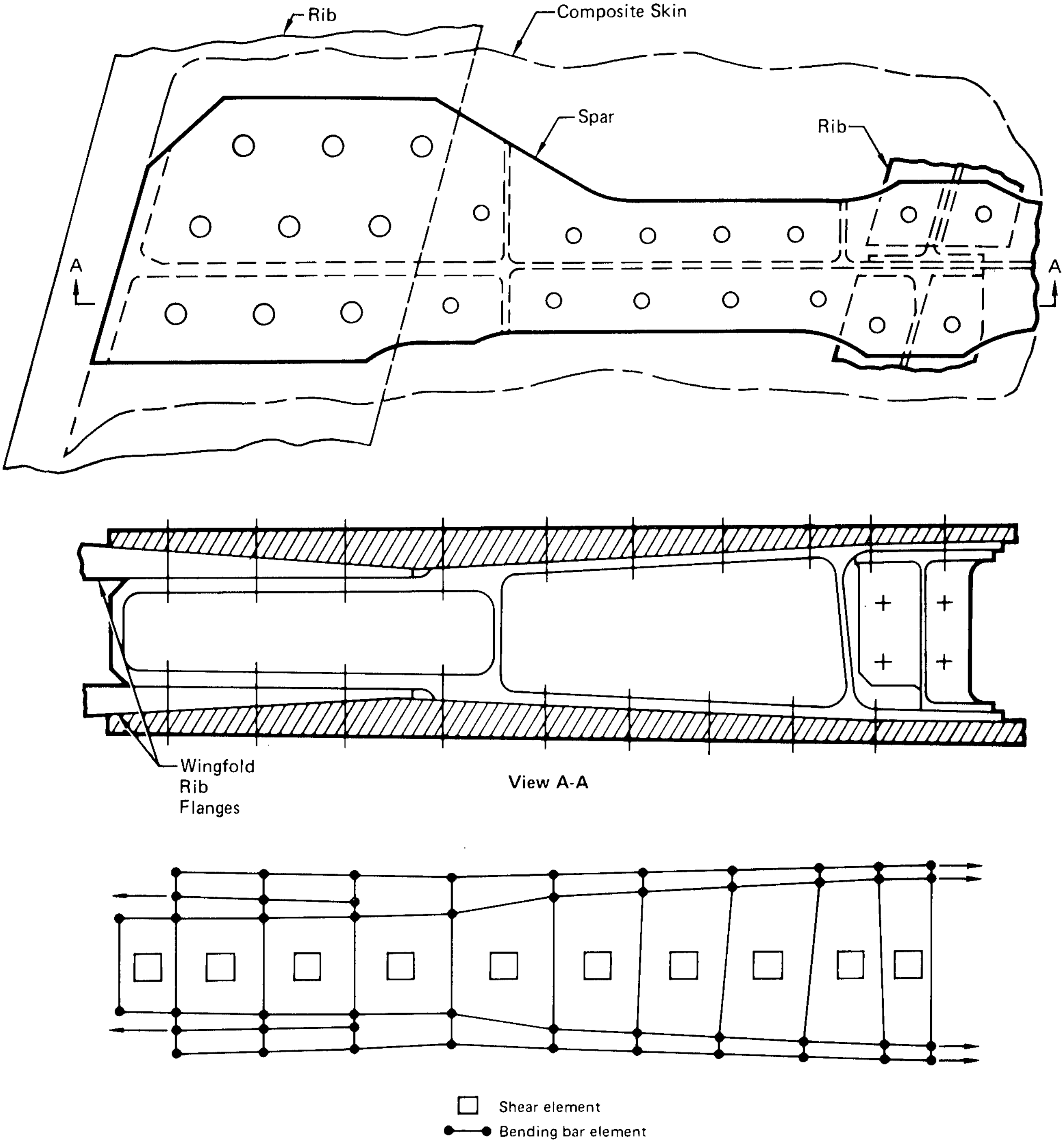


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FIGURE 9

WINGFOLD SPLICE JOINT IDEALIZATION

isotropic metal data available, or calculated using formulae developed for thin sheet metal (References 12, 15). Recently, Ojalvo (Reference 13) used a combination of finite element analysis in conjunction with short beam-on-elastic-foundation theory to analytically predict single-fastener load deflection behavior. Although applied to metal members, this analytic model may be applicable to composites. Additional development of empirical or analytic methodology for composite joints is needed to avoid excessive experimental characterization.

Friction also significantly affects joint bolt load distribution. Friction between plates reduces loads on the fastener shear faces and end-bolt loading peaks for multi-bolt joints. However, friction is usually conservatively ignored in joint analysis because frictional forces in a joint are dependent on bolt torque which cannot be guaranteed over the life of a structural splice.

Generally sufficient geometric complexity exists in most structural joint configurations such that force and displacement numerical methods are routinely employed with structural idealizations composed of simple finite elements (e.g. bending bars and shear elements were used in the wing-fold splice shown in Figure 9). Recently, interactive graphic (Reference 16) procedures have improved the development of large finite element models, and smaller special purpose finite element analysis programs are also available. Consequently, structural idealizations can be increasingly realistic with respect to geometry, material properties, and applied loadings.

These analytic and numerical techniques provide sufficient capability to accurately predict individual fastener shear plane load distributions and by-pass loads at fastener hole locations.

c. Detailed Stress Analysis

Joint load distribution analysis requires determination of the stress distributions in the immediate vicinity

of the fastener hole. Theoretical and empirical methods are currently utilized in the industry. The objective is to accurately account for very local load distributions or "stress concentrations" caused by the presence of the fastener hole. Gross external loads acting on the element of material surrounding the fastener are determined from overall structural analysis and one-dimensional splice analysis. These loads, which may include general biaxial by-pass stresses and fastener bearing loads, usually do not align with principal material axes (Figure 10).

Theoretical Approaches - State-of-the-art theoretical approaches include analytic, finite element, and strength of materials approximation methods. Analytic methods (References 17, 18, and 19) are preferred because they are economical, more amenable to parametric studies, and generate continuous solutions between imposed boundary conditions. Finite element methods (References 13 and 20) permit solutions to be obtained for complex joint geometries but are approximations to the actual problem solution throughout the entire model. Continuous or exact solutions can be approached through finer grid modeling but this is more expensive for single point and parametric studies. Strength of materials approximation methods (References 21 and 22) generally utilize one-dimensional models using beam analogies or shear lag theory. While giving insight to overall load distribution behavior, failure analysis for general loadings based on this restricted form of joint modeling does not seem possible.

Analytic Methods - These methods are principally formulated from two-dimensional anisotropic elasticity theory. Initially, fasteners were modeled as rigid inclusions in infinite plates (Reference 23) similar to metal analysis. Recent improvements center on modeling fastener radial load distributions while neglecting fastener frictional shear forces at the hole boundary. Two models have been investigated: (1) a radial stress boundary condition

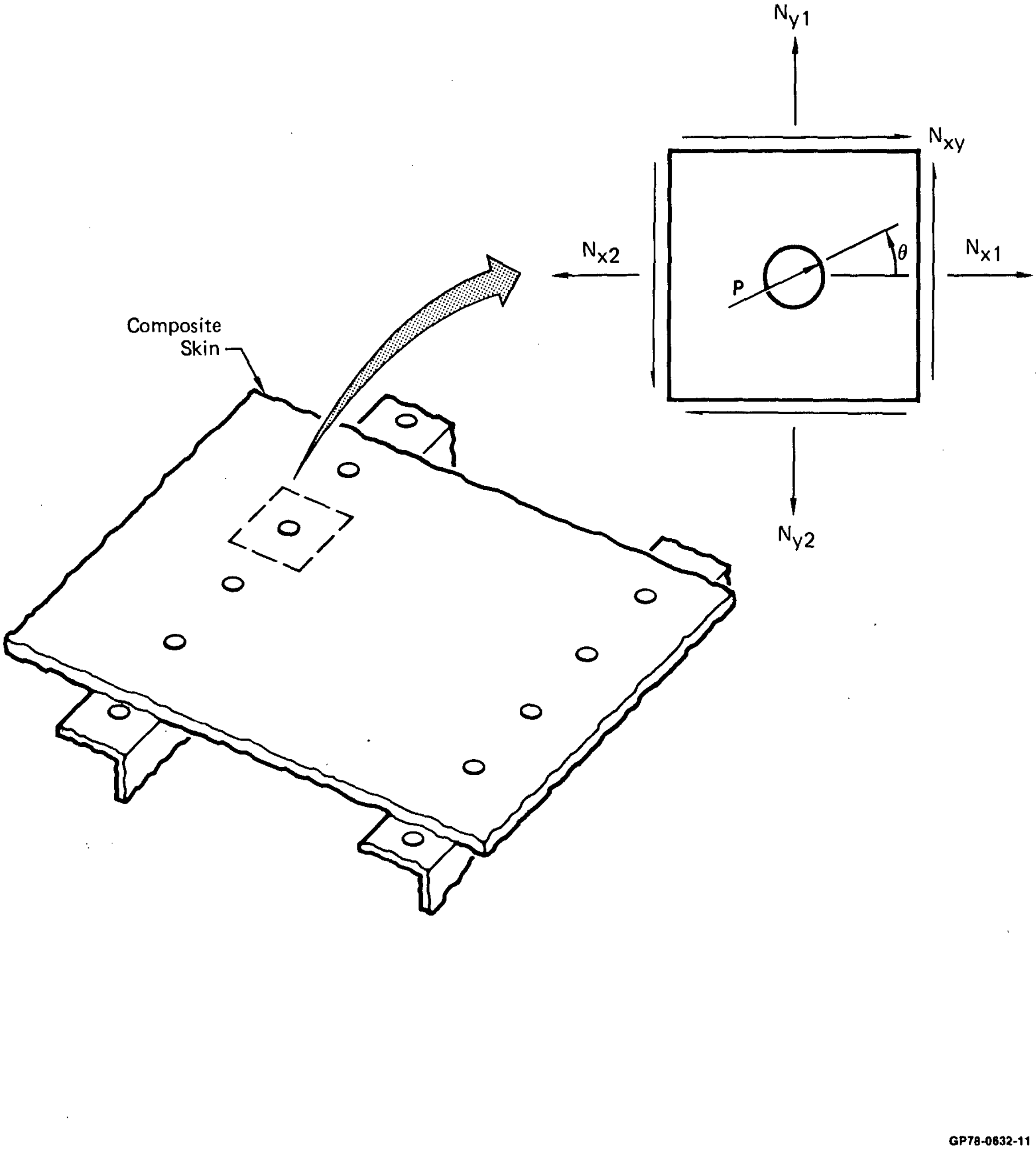

FIGURE 10
GENERAL LOADING AT INDIVIDUAL FASTENER HOLES

varying in a cosine distribution (Reference 17), and (2) a radial displacement boundary condition corresponding to rigid displacement of the fastener coupled with a solution of the associated contact problem (Reference 18).

Oplinger and Gandhi (References 18 and 24) and Oplinger in a recent review of analysis methods (Reference 25) compare the two models. Predictions of radial stress distributions were obtained by modeling fastener loading as a rigid displacement of the fastener. Figure 11, taken from Reference 24, illustrates that little difference from half-cosine stress distributions occurred for large width and edge geometry. However, radial stress distributions show considerable differences relative to a half-cosine distribution at smaller width and edge distances. Additionally, Oplinger examined radial stress distributions resulting from a range of by-pass load to bearing load ratios existing at a single fastener hole. Resulting radial stress distributions are significantly different from half-cosine distributions as by-pass loading increases. Figure 12 taken from Reference 25 indicates that by-pass loads cause a loss of contact in front as well as behind the fastener for low bearing loads as compared to the pure bearing case. This result was also reported by DeJong (Reference 19).

Effects of fastener hole friction were also evaluated in Reference 24 for friction coefficients ranging from 0.0 to 0.5. Resulting radial stress distributions at $\theta = 0$, Figure 13, were less than half of the stress distribution with no friction.

Oplinger's results (Reference 25) were obtained utilizing two-dimensional anisotropic elastic analysis consisting of a complex variable formulation in conjunction with a least-squares boundary collocation scheme. Iteration techniques were used to solve the non-linear contact boundary conditions of this problem. This analysis addressed loaded holes with uniaxial loads aligned with principal material axes.

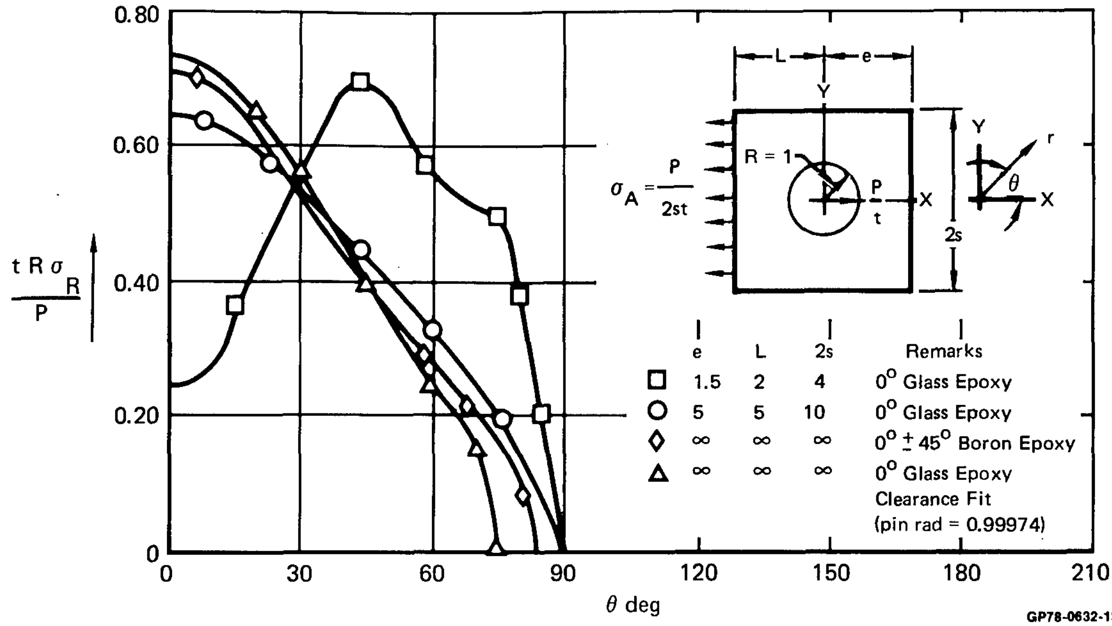

FIGURE 11
RADIAL STRESS DISTRIBUTIONS AROUND FASTENER HOLE

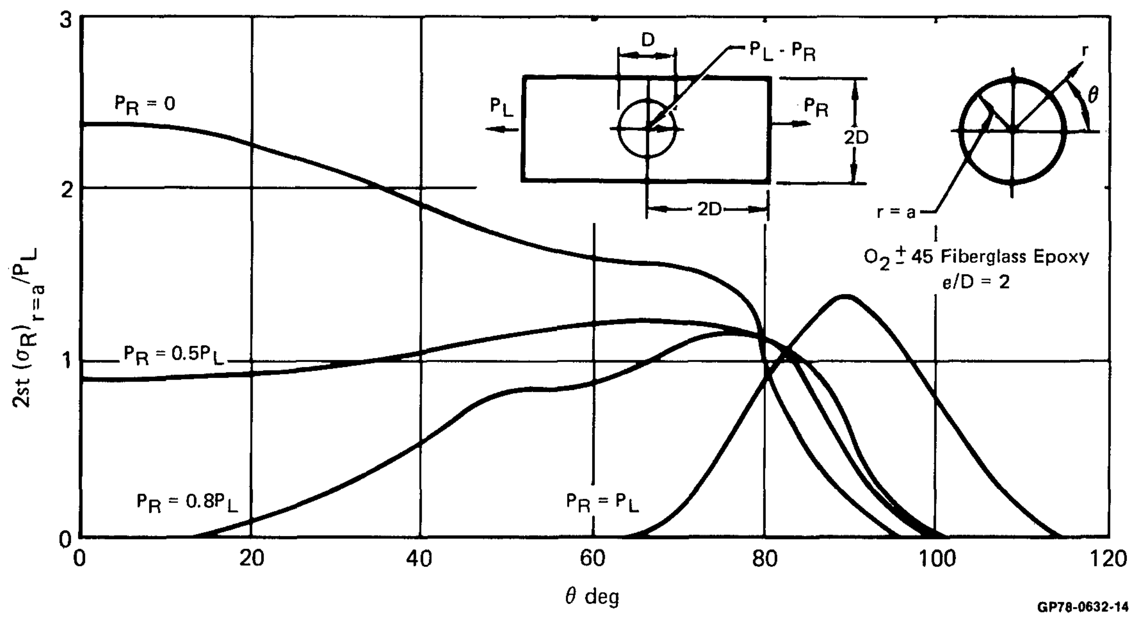

FIGURE 12
RADIAL STRESS DISTRIBUTION AROUND PARTIALLY LOADED FASTENER

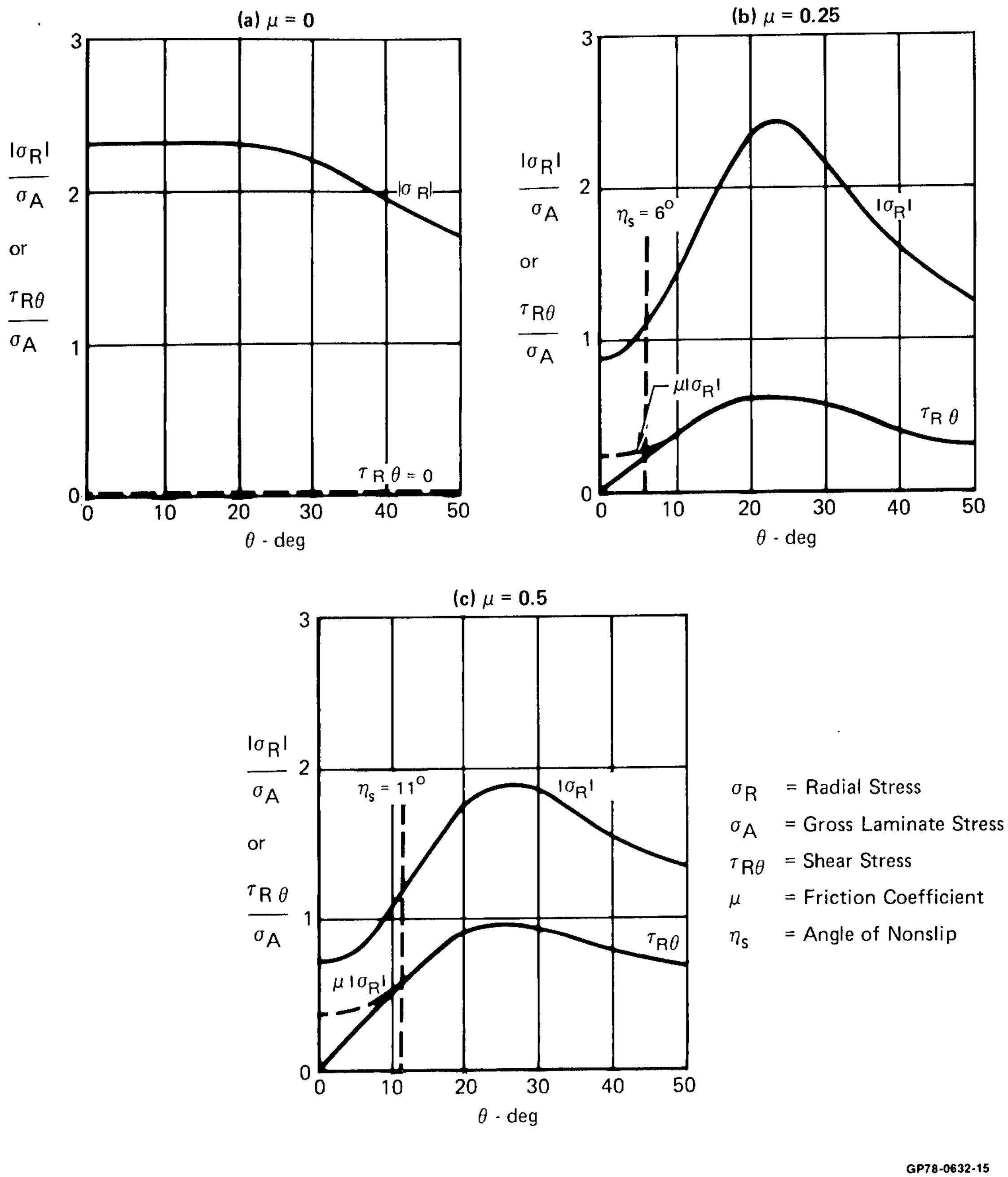

FIGURE 13

EFFECT OF FRICTION ON RADIAL AND SHEAR STRESS DISTRIBUTION AROUND FASTENER HOLE, $O_2 \pm 45$ GRAPHITE EPOXY, e/D = 4, s/D = 1 (MULTI-PIN)

Prior to Oplinger and Gandhi, Waszczak and Cruse (Reference 17) examined the importance of assumed fastener radial stress distributions from a different viewpoint. Assuming different cosine series distributions, the effects of these variations were assessed with respect to resulting hoop stresses surrounding the fastener hole. They concluded that no significant difference in hoop stress distributions resulted. Thus, their mathematical models use exclusively a half-cosine radial stress boundary condition to simulate bolt loading. Their analytic methods consisted of two-dimensional anisotropic elasticity in conjunction with a boundary-integral equation solution technique (Reference 26). Analysis accounted for loaded holes, orthotropic material behavior, and finite geometry. Loadings were limited to uniaxial loads aligned with principal material axes.

Eisenmann (Reference 27) proposed a fracture mechanics model which treats the loaded hole problem under general in-plane fastener loadings. Material anisotropy and finite geometry are accounted for in this model. Analysis utilizes classical anisotropic elasticity theory in conjunction with the boundary integral equation solution techniques of Reference 26. A cosine distribution of radial stresses due to bolt loading was assumed. Solutions for finite geometry and orthotropic laminates are used as corrections to infinite plate stress concentration factors at eight discrete points along the fastener boundary (every 45 degrees starting at a principal material axis). An apparently empirical formula is then used at each discrete location to correct isotropic Mode I stress intensity factors for orthotropic material behavior. Corrected intensity factors are then used in conjunction with a fracture hypothesis and fracture toughness data to predict laminate failure. Complex loads are handled through the use of elastic superposition principles as applied to fracture mechanics calculation of Mode I stress intensity factors. It is assumed in this method that failure will initiate at one of the eight discrete points on

the hole boundary.

A Bolted Joint Stress Field Model (BJSFM) has been developed at McDonnell Aircraft (Reference 28). This model utilizes two-dimensional elastic anisotropic theory to predict laminate stress and strain distributions around an unloaded or loaded fastener hole in orthotropic materials. This methodology has been incorporated into a user-oriented computer program entitled "BJSFM". Variables accounted for in this programmed analysis include material strength anisotropy, stiffness anisotropy, general bi-axial inplane loadings (tension, compression, shear), general fastener loadings, multi-material (hybrid) laminates, and arbitrary fastener hole sizes. Bolt bearing loads are represented by a cosine distribution of radial stresses at the fastener hole. Solution data is available on a laminate or per ply basis in terms of stress or strain distributions. Failure analysis on a ply-by-ply basis is performed utilizing user designated failure criteria. Automatic search routines review complete stress or strain distributions to determine critical plies and failure locations.

Finite Element Methodology - This methodology is limited only by the number of elements which can be economically justified. Idealizations of mechanically fastened joints can be created to provide solutions comparable to the analytic methods described earlier in this report; however, costs and facility in utilizing this numerical method for parametric studies usually limits its use. The effects of varying fundamental parameters are determined using closed form analytic methods, while complex geometry variables associated with multiple hole fastener patterns or complex third dimension effects (e.g. through-the-thickness bearing distributions) are evaluated using finite element idealizations. Additionally, finite element results can be used to verify the accuracy of newly developed analytic methods. Utilization of finite element methodology in joint analysis is discussed in References 10, 17, 20,

and 29 and can be considered state-of-the-art.

Strength of Material Approximation Methods - While providing considerable physical insight, approximation methods (e.g. elementary beam theory, shear lag theory) are too limited to account for loading complexities and material orthotropy found in composite structural joints. An exception arises when finite element methods, analytic methods, and strength approximation methods are interacted. Recently, Ojalvo (Reference 13) used finite element analysis in conjunction with short beam on elastic foundation theory (Figure 14) to analytically predict single-fastener hole deflection behavior for metallic joints. This analytic model may be applicable to composites. Variables including fastener flexibility, head rotation, countersink effects, through-the-plate thickness variation of stress, and non-uniform foundation modulus were accounted for in this model. Some through-the-thickness effects revealed using this model are summarized in Figures 15 and 16 taken from Reference 29. None of the analytic methods previously discussed can account for these variables.

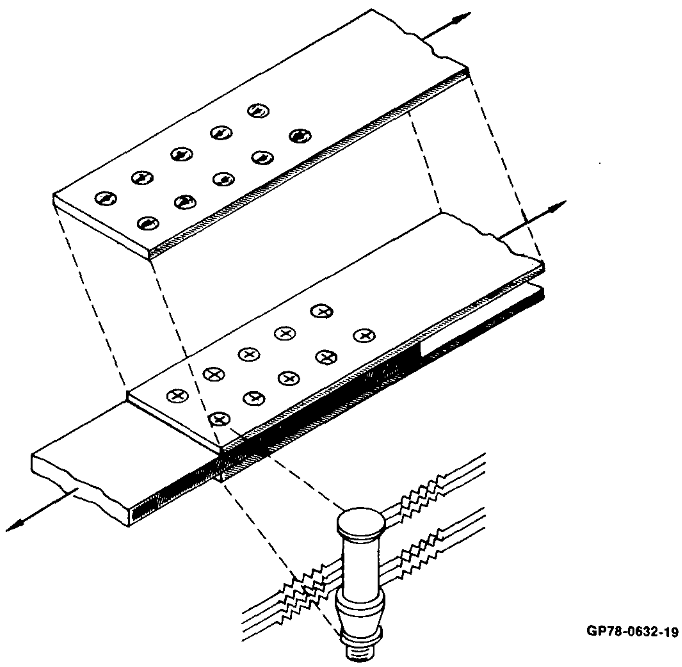

FIGURE 14
SHORT BEAM ON ELASTIC FOUNDATION MODELING SCHEME FOR THROUGH-THE-THICKNESS EFFECTS

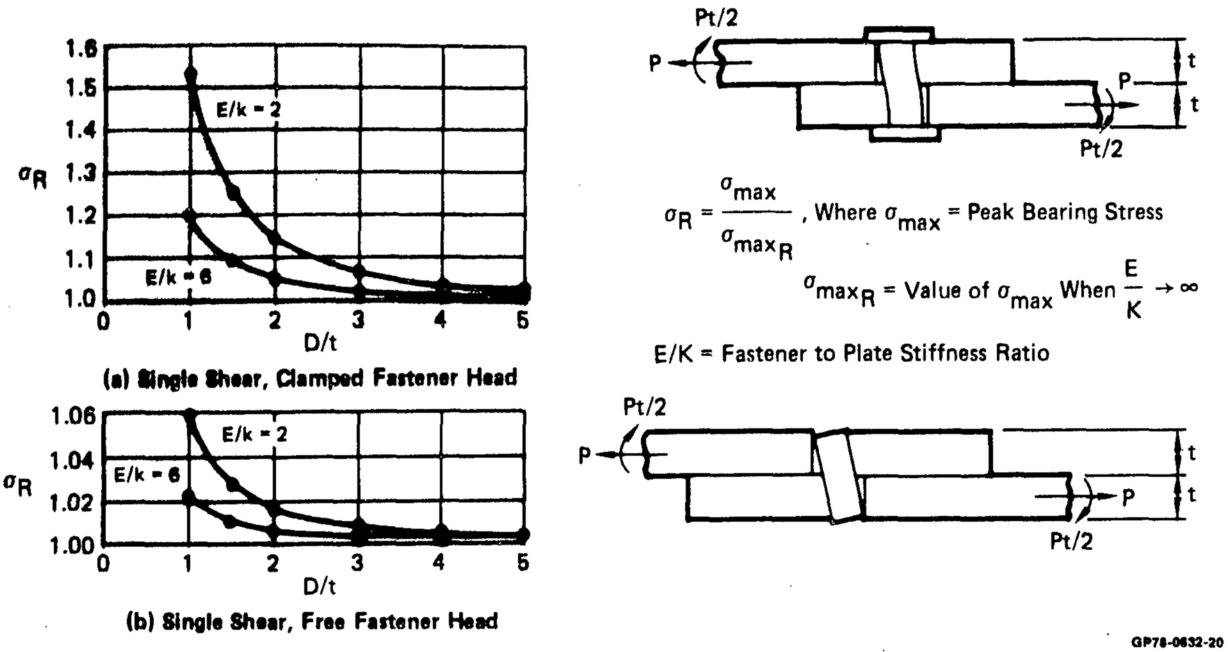

FIGURE 15
EFFECT OF FASTENER STIFFNESS ON PEAK BEARING STRESS

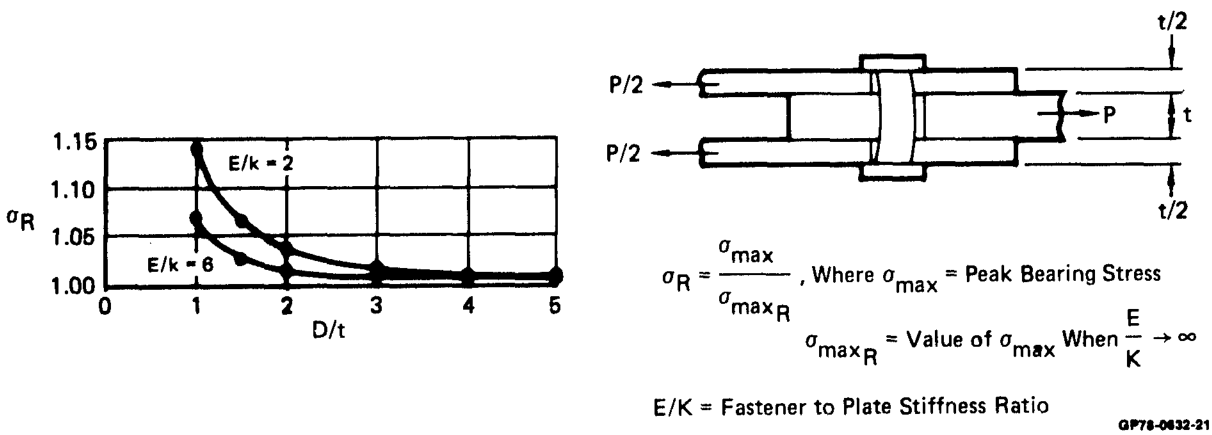

FIGURE 16
EFFECT OF FASTENER STIFFNESS ON PEAK BEARING STRESS-DOUBLE SHEAR CASE WITH ARBITRARY FASTENER HEAD END CONDITIONS

Empirical Approaches - State-of-the-art empirical approaches represent an alternative to detailed stress distribution analysis by assessing failure directly through tests on design oriented composite specimens. Variables of geometry (e.g. width, edge distance, load eccentricity, countersinking) are specified over a design range of interest and specific tests can be performed. Other variables, such as percent of load transferred through bearing and by-pass are likewise tested directly. A variety of lay-ups are usually specified in an attempt to account for the application realm of possibilities.

Hart-Smith's work (Reference 30) is an example of a comprehensive experimental evaluation of bolted joints in graphite-epoxy composites. Empirical analysis methods are presented for design of bolted composite joints. Uniaxially loaded joint design strengths are related to gross or net section levels through load-interaction curves (e.g. by-pass versus bearing - Figure 17). For any one laminate, these design curves account for stress concentration effects on strength ranging from unloaded fastener holes to loaded fastener holes where all load is transferred in bearing. Strength variation due to lay-up are accounted for by strength carpet plots (e.g. Figure 18) which delineate joint failure modes of shear-out, net section, and bearing. Empirical formulae are specified and design-analysis procedures are outlined.

The application of this approach is limited by testing costs. Generally, it is limited to uniaxial loadings because test variations become too numerous for consideration of general biaxial loadings and arbitrary fastener load direction. Empirical methodology was not found for general bi-axial inplane-loadings and arbitrary fastener load directions. Additionally, each change of material system requires a complete repetition of all testing.

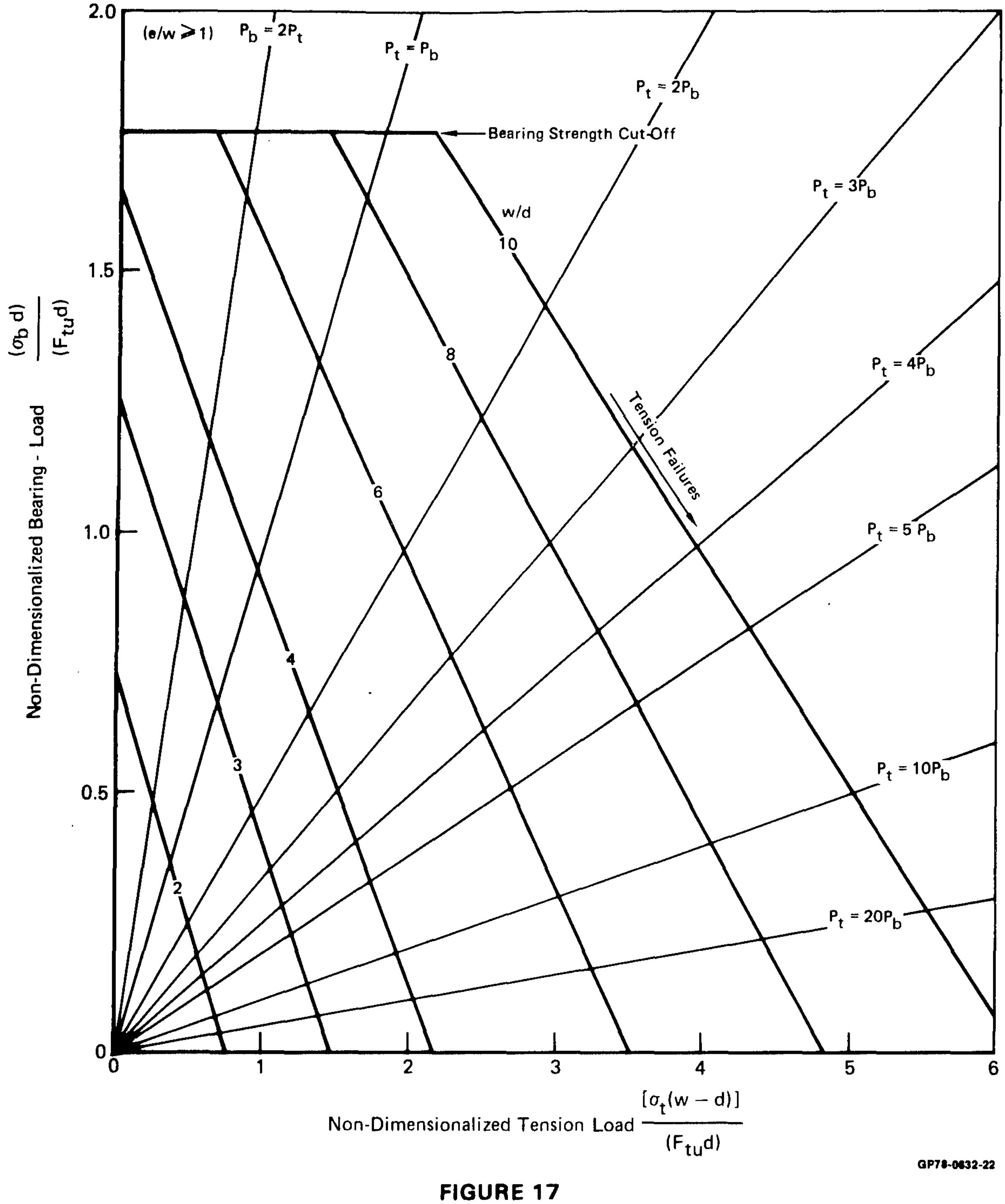

FIGURE 17
CALCULATED INTERACTIONS BETWEEN BEARING AND TENSION LOADS ON TWO-ROW BOLTED JOINTS IN GRAPHITE-EPOXY COMPOSITES

point stresses within a structural material. In the latter context criteria such as Tsai-Hill, maximum strain, maximum stress, Tsai-Wu, etc., are used for composite materials. Both types of failure analysis are discussed below.

Composite members in bolted joints differ from their metal counterparts primarily in their anisotropic strength and stiffness properties, and lack of ductility. Lack of material ductility limits ability of structure to beneficially redistribute fastener loads in multiple-fastener composite joints and limits redistribution of locally high stresses at points of stress concentration. In addition, inherent interlaminar weaknesses relative to metals results in unique and complex failure modes as illustrated in Figure 19.

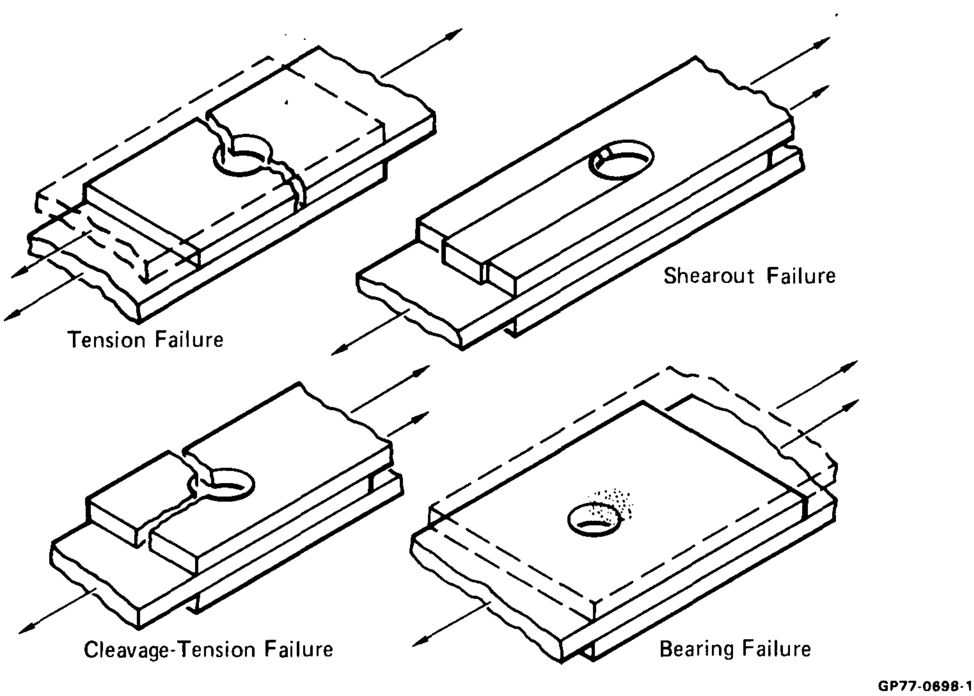

FIGURE 19
MODES OF FAILURE FOR BOLTED COMPOSITE JOINTS

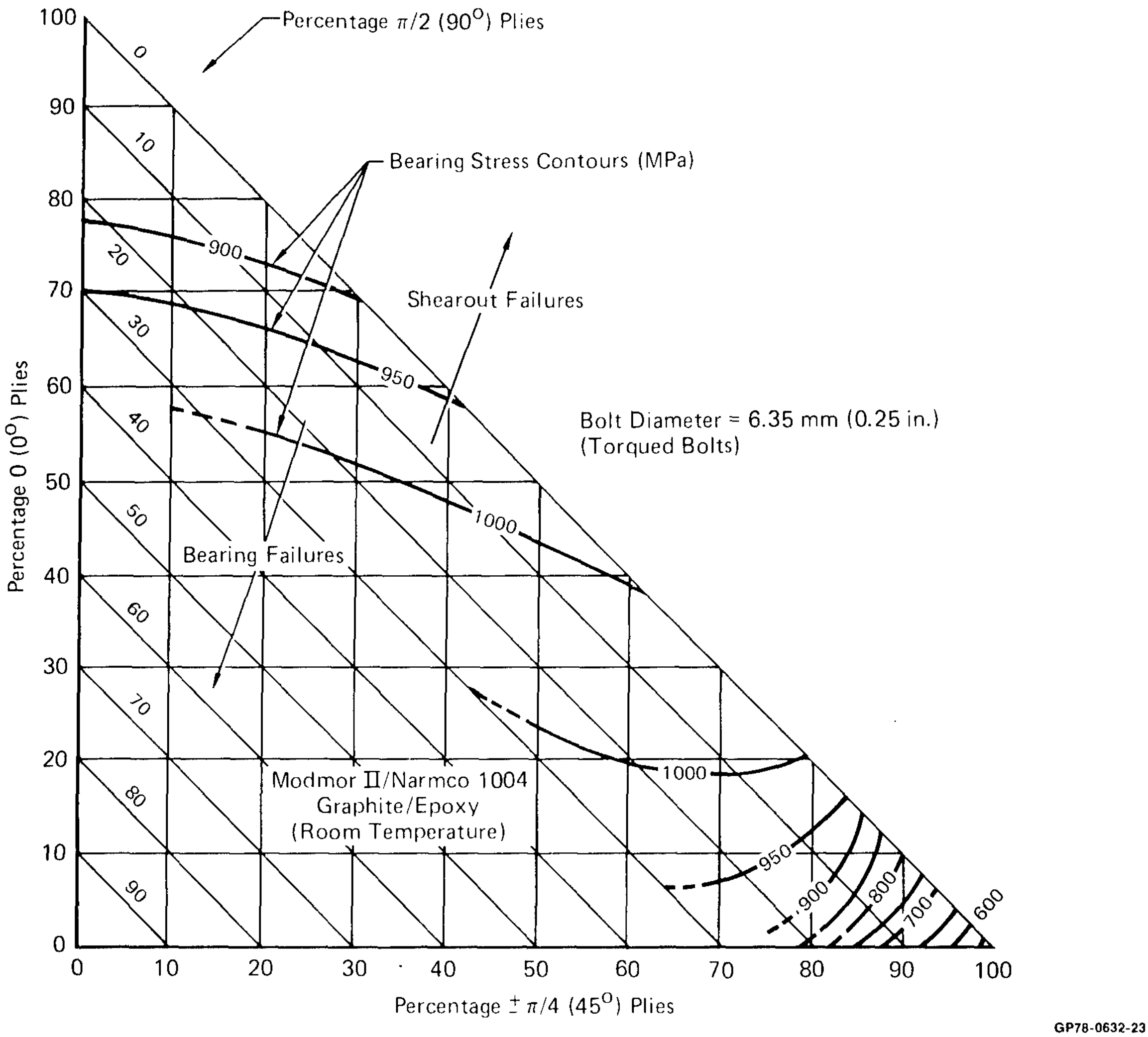

FIGURE 18

BEARING STRESS CONTOURS FOR VARIOUS LAMINATE PATTERNS MODMOR II/NARMCO 1004 GRAPHITE-EPOXY COMPOSITE

4. JOINT FAILURE ANALYSIS

Joint failure analysis as used in this section is defined as an analytic model or distinctive methodology which is used to predict failure mode, failure location, and failure load at any one fastener hole contained in a bolted composite joint. Material failure analysis may be concerned solely with prediction of unnotched material failure from

Joint failure analysis must fully account for effects of local laminate behavior at the edge of fastener holes, as well as material anisotropic strength and stiffness. Composites exhibit little overall material plasticity and stress concentrations are a dominant factor limiting static strength. Analysis of anisotropic stress concentration effects has been shown to be highly conservative, with theoretical elastic stress levels being approximately 25-50% higher than strength test data would indicate for loaded or unloaded holes. Figure 20 compares elastic stress concentration predictions with MCAIR experimental data. Although composites are thought to have little ductility, an effective stress concentration relief phenomenon at the boundary of the fastener hole has a beneficial effect on strength. Oplinger (Reference 25) suggests this effect may be attributed to non-linear composite shear behavior. Daniel (Reference 31) has experimentally observed localized and progressive ply damage initiating at the hole boundary prior to overall laminate failure. Localized ply damage implies reduced material stiffness surrounding the hole boundary and reduced stress concentration peaks.

Laminate ⚠1	Test Data	Theoretical		Theory/Test
		Finite Element	Elasticity ∞Plate	
$(\pm 45^{\circ})_{5s}$	1.14	2.89	2.87	2.52
$(0^{\circ}, \pm 45^{\circ}, 0, \pm 45^{\circ}, 0^{\circ}, \pm 45^{\circ}, 90^{\circ}, 0^{\circ})_s$	1.71	3.20	3.17	1.85
$(0^{\circ}, \pm 45^{\circ}, 90^{\circ})_s$	1.51	3.00	3.00	1.99
$(0^{\circ}, \pm 45^{\circ}, 90^{\circ}, 0^{\circ})_s$	1.54	3.42	3.41	2.21
$(0^{\circ}_2, \pm 45^{\circ}, 90^{\circ}, 0^{\circ})_s$	1.56	3.72	3.71	2.38

⚠1 Uniaxial Loaded T300/5208 Coupon Specimens ~ Unloaded Open Hole

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FIGURE 20
THEORETICAL STRESS CONCENTRATION FACTOR IS CONSERVATIVE

Current joint failure analysis can be grouped into five classifications: (1) empirical, (2) elastic failure analysis, (3) inelastic failure analysis, (4) phenomenological failure analysis and (5) fracture mechanics models.

Empirical joint failure methods are based on tests of particular material systems, joint variables, fastener types, etc. Strength design curves are based on this data usually in terms of gross or net section stresses or strain allowables. Detailed stress distribution analysis is not required. Design allowables for variables not tested are estimated through interpolation or extrapolation procedures.

Elastic joint failure analysis utilizes methods described in Section III,3 to determine elastic stress and strain distributions surrounding individual fastener holes. Material point stress failure criteria (e.g. maximum strain, distortional energy) are then utilized to assess overall laminate failure or first ply failure.

Inelastic joint failure analyses modify elastic methods to account for localized "composite relief" or "softening" of elastic stress concentration at the hole boundary. Only finite element idealizations have thus far been utilized for solution of this problem. Brown (Reference 32) uses an iterative, elastic, first ply failure analysis to identify when certain local element stiffnesses should be considered zero. Chou (Reference 33) carries this approach further by accounting for non-linear material behavior using an iterative finite element tangent modulus approach. In both methods, loads are reapplied to the altered finite element idealization and progressive first ply failure of laminae monitored until overall laminate failure occurs. First ply failures are determined using material point stress failure criteria. Results obtained from these methods are currently limited to restricted geometries and unloaded holes.

Phenomenological approaches as defined by Wu (Reference 34) "treat the heterogeneous composite as a continuum, and

a mathematical model is used to correlate the occurrence of the material responses without necessarily explaining the mechanisms which lead to these material responses". This approach has been used to account for material inelastic or non-linear behavior at the hole boundary, while permitting utilization of elastic anisotropic stress analyses. Whitney and Nuismer (Reference 35) have postulated that failure of a composite material with a stress concentration can be associated with point stresses or average stresses at or within a "characteristic dimension" from the edge of a stress concentration (Figure 21). This postulate appears to be a specialization of the "characteristic volume" concept discussed by Wu (Reference 36).

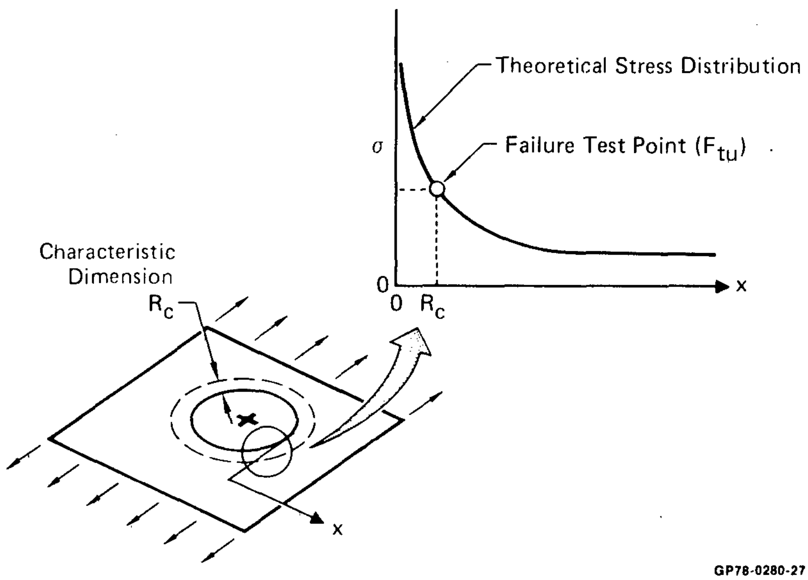

FIGURE 21
FAILURE HYPOTHESIS

The MCAIR-developed "Bolted Joint Stress Field Model" (BJSFM) generalizes the characteristic dimension concept to anisotropic laminates for general biaxial by-pass and fastener loads, and eliminates the need to test each laminate

analyzed. Laminate failure is assessed on a ply-by-ply basis at a characteristic dimension away from the hole boundary. Ply failures are assessed utilizing user-designated material failure criteria which are contained within the BJSFM program. Only elemental testing of the basic lamina (unidirectional ply) of any one material system, and one laminate configuration are required for strength predictions. Independently, Lo (Reference 37) presented results obtained from a similar utilization of the characteristic dimension concept.

A linear elastic fracture mechanics model (Reference 27) has been utilized to create a method for predicting static strength of bolted composite joints. Following Reference 37, this method assumes an "intense energy region", characterized by a critical crack length (a), must be stressed to a critical level before fracture occurs. Empirical equations are used to determine radial crack lengths for an arbitrary laminate. Bolted joint laminate strength is assessed at the specified radial crack tip by comparing calculated mode I stress intensity factors (K_I) with experimentally determined laminate fracture toughness (K_Q). Failures are assessed at eight discrete locations around the bolt hole boundary (every 45° starting at a principal material axes). Orthotropic mode I stress intensities are calculated using an empirical formula which corrects isotropic results for orthotropic material behavior. All analysis is performed on a laminate level. Considerable laminate test data is required to characterize the variation in laminate fracture toughness at the selected points on the hole boundary.

In each of the five classifications (Section III, 4) of joint failure analysis, after stress or strain distributions are determined, material strength is assessed by utilization of material point stress failure criteria. Except for fracture mechanics models which utilized mode I fracture tough-

ness data, no single material failure criteria is uniformly endorsed by any of the method originators. The following paragraphs present a general overview of material failure criteria.

Anisotropic material failure criteria are numerous. Sandhu (Reference 39) lists twenty-one distinct material failure criteria or anisotropic theories of strength. These theories are classified according to their failure mode interactions. Five are defined as having no interaction of failure modes (e.g. maximum strain criterion, maximum stress criterion). Sixteen contain various degrees of failure mode interaction (e.g. Von Mises-Hill Criterion, Tsai-Wu Criterion). Generally, when failure mode interaction exists, a smooth and continuous quadratic failure envelope is generated in each load quadrant, while no failure mode interaction results in points of failure envelope discontinuity.

Degree of material strength anisotropy is accounted for by the number of independent parameters necessary to generate a particular failure envelope. Each parameter is generated by a separate strength test of the laminate in question. Most orthotropic material failure criterion require five independent strength tests; pure shear, and tension and compression along each of the principal material axes. Tsai and Wu (Reference 40) suggest that an additional independent test under biaxial loading is required to accurately specify orthotropic failure envelopes.

In Reference 34, Wu presents a comprehensive theoretical examination of anisotropic material failure criteria. Model fundamental requirements are listed and a comparison of frequently used criteria is made. Experimental techniques and data analysis are also discussed. Wu concludes that stress or strain tensor-polynomial formulations of material failure criteria meet "fundamental mathematical requirements" and "encompasses maximum flexibility". Additionally, most material failure criteria presently used can be derived from tensor-polynomial forms. Later, in References 41 and 42,

utilization of these lamina failure envelopes is extended to general laminate construction, and a more general tensor-polynomial form is postulated with higher order terms.

Cole and Pipes (Reference 43) generated considerable biaxial test data for graphite-epoxy and boron-epoxy material systems. Results were correlated with three material failure criteria: 1) maximum strain, 2) Hill, and 3) Tsai-Wu. Their general conclusion was that none of the material strength criteria were adequate in all cases. However, a high degree of scatter in their strength data reduces confidence in this conclusion. Wu's data (Reference 34) favored the tensor-polynomial form. Tennysen (Reference 44) performed biaxial tests solely to evaluate the applicability of the tensor-polynomial criterion. Resulting conclusions state that for arbitrary laminate orientations, the quadratic form of the tensor-polynomial is too conservative; while the cubic form of the tensor-polynomial provided accurate failure load predictions.

Sandhu (Reference 45) utilizes a cubic spline interpolation technique to account for material non-linear stress-strain response. Laminate response under load is then predicted using an incremental constitutive law. Laminate failure is predicted using a material failure criterion based on failure strain energies under longitudinal, transverse, and shear loadings as independent parameters. Analytic results compared with limited test data in Sandhu's report tended to favor this technique.

Direct studies regarding utilization of various material failure criteria for joint failure analysis is very limited. Waszczak and Cruise (References 17 and 46) reported on an evaluation of three material failure criteria, 1) maximum stress, 2) maximum strain, and 3) Tsai-Hill Criterion. Using contour plots of failure levels for each ply in a variety of laminates, correct failure modes were predicted in all but shear-out cases. Their conclusion was that while failure loads could be predicted using all three failure criteria,

only the Tsai-Hill Criterion provided accurate failure load and failure mode information. Oplinger (Reference 25) likewise suggests that a quadratic failure envelope (Hoffman Criteria - Reference 39) is preferred for failure mode analysis in bolted composite joints. Analysis (Reference 30) which depends on empirically derived formulae use a variation of maximum stress or maximum strain criterion; this usually implies that effects of load interaction (e.g. Poisson's effect, biaxiality) are neglected.

Qualifying assumptions usually accompany the utilization of a particular material failure criteria. These assumptions arise due to experimental observation of failure modes, inelastic material behavior, recognition that certain ply failures may not result in overall laminate failure. Examples found in the literature include: ignoring matrix failures in individual lamina when adjacent laminae have fibers oriented in the transverse direction (Reference 15), and assumptions concerning local compression bearing failure at fastener holes (Reference 17).

5. FATIGUE LIFE METHODOLOGY

The purpose of this segment of the literature survey is to review the state-of-the-art fatigue life methodologies used for predicting composite fatigue behavior. Most current methods have been derived based on an extension of metallic (isotropic) failure theories.

In reviewing the literature, fatigue life methodologies were identified which are currently used or are being developed throughout the industry. Most documented information cited has been experimental investigations of composite fatigue with little attempt to derive methodology to predict observed failure modes and data trends. These investigations have pointed out design variables which affect fatigue life of composite materials. A generalized fatigue life methodology should, of course, consider as many design variables as possible including composite material system, lay-up, geometry and fatigue loading conditions (stress ratio, fre-

quency, etc.). A failure analysis procedure to predict structural life is also necessary.

In the literature reviewed, there were basically three approaches taken to analyze composite structure subjected to cyclic loading. These methods can be categorized as (1) empirical correlations, (2) cumulative damage models, and (3) fracture mechanics analysis. Of the analytical techniques that have been developed, few have had extensive experimental verification of their accuracy. In the following paragraphs is a discussion of methods used for predicting fatigue life of composite structure.

Empirical Methods - Current state-of-the-art of life prediction approaches is to conduct spectrum fatigue tests on specimens representative of specific design details. These empirical techniques are still widely accepted due to lack of confidence in and verification of analytical fatigue life prediction techniques. In meeting various military durability specifications (MIL-A-8866, MIL-A-83444, etc.), all current and near term military aircraft (B-1, F-15, F-16, F-18, AV-8B) are using empirical methods to assess the effects of cyclic loading on composite life (References 5 and 47). These investigations have demonstrated that sufficient fatigue life is achieved by composite structure designed to satisfy static strength requirements.

Most research and development programs on composite fatigue have also emphasized experimental investigations. Conclusions and recommendations reached in these studies have been based on empirical curves fit through data. Test data has shown that fatigue failure modes are not typically the same as static modes of failure (References 48 and 49). Extrapolation of these curves is difficult due to the lack of physical understanding of the failure mechanisms involved.

Inherent with empirical methods is the large data base needed to generate them. Most published fatigue data have been on unnotched laminates or laminates with an unloaded hole. Relatively little fatigue data exists on bolted composite

joints. Of the existing data, results are often for specialized specimen design, layup or test conditions.

Cumulative Damage Models - Cumulative damage models have been used in predicting fatigue life of metallic structures. These models are based on the assumption that a portion of the structure's life is depleted with each application of load. Spectrum fatigue life predictions are characteristically accomplished by analyzing the loading as blocks of equivalent constant amplitude load levels and stress ratios.

Linear and non-linear summation models have been postulated and used for metals. To date, only linear models have been applied to composites. Miner's linear cumulative damage rule has been the most-explored cumulative method for analyzing composites. Miner's rule is simple to use. It requires only constant amplitude fatigue data (S-N curves) for the applied stress ratios in the spectrum (Figure 22). There is currently no validated technique for predicting (correlating) the effects of stress ratio on composite fatigue life. This technique is required to permit prediction of spectrum life, without resorting to extensive stress ratio testing. Miner's rule is also geometry-dependent. The S-N data required must be generated from the same specimen geometry as used in spectrum tests.

Attempts to use Miner's rule have met with varying degrees of success. In some cases, it has been reported that Miner's rule is grossly unconservative in predicting life of composite materials (References 20 and 50). Others have found it to be an adequate technique for preliminary design studies (References 51 and 52). A limited investigation at MCAIR indicated that Miner's rule is adequate to gauge the severity of spectra variations.

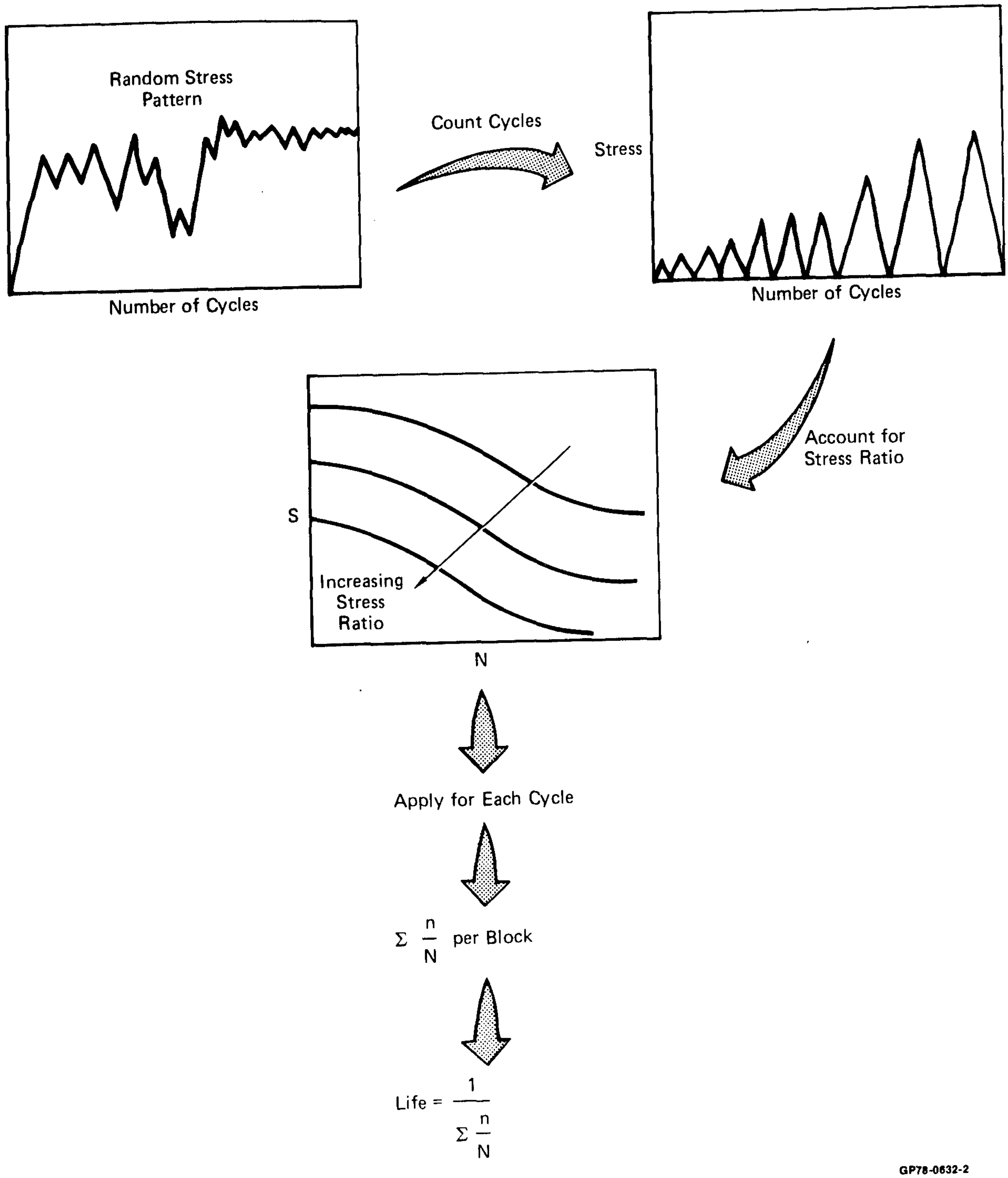

FIGURE 22
MINER'S RULE APPLIED TO COMPOSITES

Fracture Mechanics Analysis - Fracture mechanics techniques have been utilized, with success, to analyze metallic structure fatigue. Due to this relative success, most analytical techniques developed to predict fatigue life of composite materials have been based on fracture mechanics techniques. The basic assumption of fracture mechanics is the existence of initial internal flaws within the material system. Flaws are assumed to grow in a deterministic manner with the application of cyclic loading. At the point of instability, fast crack propagation and fracture occur.

Various analytical procedures based on these assumptions have been developed for composite laminates. Of documented composite fatigue life methodologies, the "wear-out model" (Reference 53) has had considerable evaluation. This model assumes the damage growth rate can be characterized by residual strength testing after cyclic loading. A growth rate equation relates both life and residual strength distributions to the initial static strength distribution. Weibull statistical analysis is used with static and residual strength test data to obtain needed shape and scale parameters for the wear-out model.

Using the wear-out model requires experimental determination of parameters needed for formulation of residual strength predictions. These include the static shape parameter, static scale parameter and the fatigue shape parameters. "Maximum likelihood estimates" (Weibull estimates) of these static parameters are determined using static test results. To determine the fatigue shape parameter, it is necessary to have fatigue failure data (life-time data) for each fatigue variable. The wear-out model generates probability-of-survival curves for a given spectrum. Estimates of specimen lifetimes for the spectrum loading are made based on wear-out model predictions as shown in Figure 23.

The wear-out model, as an analytic tool, has limitations. It is primarily an empirical procedure which applies to a restricted set of experimental results. Each new

configuration must be fatigue tested to determine parameters needed in the wear-out equation. The wear-out equation as derived is also a monotonically decreasing function of time and is incapable of predicting increases in residual strength which have been found to occur in composite structure (Reference 54). The accuracy of the model for stress level shifts is dependent on failure modes remaining constant. Spectrum modifications may cause failure modes which are not the same as the structure for a baseline spectrum. Ryder (Reference 55) has done an extensive investigation of the wear-out model. He states that "... the real value of any formulation to describe the wear-out or strength degradation rate is to accurately predict the time to first failure of coupons or components undergoing fatigue loading at different stress levels than those previously used to obtain life data. The data from this report indicates that any such prediction based on the wear-out model as formulated above would have a low accuracy and thus little utility. ... The model is inadequate beyond satisfaction of the boundary conditions."

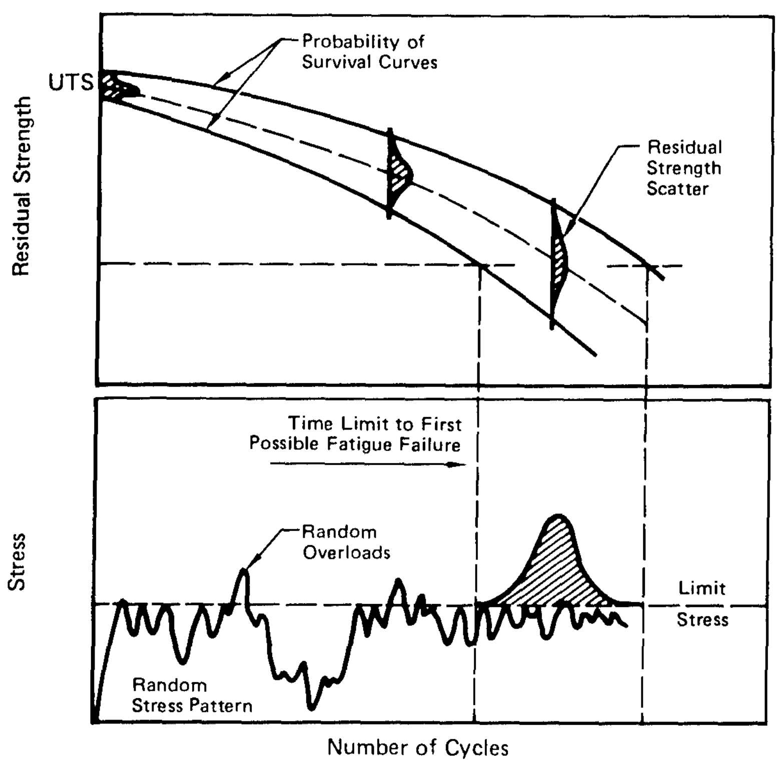

FIGURE 23
WEAR-OUT MODEL ANALYSIS

Yang derived a residual strength degradation model (Reference 56) to predict fatigue life of composites which is similar to the wear-out model. Yang's model was derived based on the assumption that residual strength is a monotonically decreasing function of number of load cycles, whereas in the wear-out model, strength degradation was based on the assumption of crack propagation. Like the wear-out model, predictions of residual strength and life are generated utilizing Weibull statistical procedures. Parameters needed in the analysis are derived from static and constant amplitude fatigue (S-N curves) test data. Once these parameters are derived, probability of survival curves, similar to those shown in Figure 23, may be generated. Analysis procedures account for tension-tension and tension-compression constant amplitude cyclic loading.

Since Yang's residual strength degradation model is a statistical approach, a large data base is needed to accurately determine parameters used in the derivation. Due to sample size limitations, these parameters are obtained through minimizing the mean square difference between various statistical equations. Slight variations in required test data result in one of these parameters varying by orders of magnitude. This indicates the sensitivity of the residual strength degradation model to data scatter. These parameters are calculated for specific situations and have no physical significance.

The basic assumption of a continuously decreasing residual strength is questionable since there is evidence showing that initial residual strength increases in many configurations. Yang has recognized this fact and stated (Reference 57) that "Under such a situation, it is recommended that a different theoretical model should be developed".

McLaughlin et al (Reference 58) derived an analytical model which theoretically can predict residual strength increases. The analysis predicts failure of a laminate having

a stress concentration (unloaded hole) from unidirectional material fatigue properties. Residual strength is treated as a static failure utilizing fatigue-degraded lamina properties. A fatigue failure occurs when the residual strength of the laminate falls to the level of applied maximum cyclic stress. The fatigue analysis methods consist of the following:

(1) Calculating laminate stresses for a given tensile loading.

(2) Performing a laminate analysis to obtain lamina stresses.

(3) Computing fatigue-induced material property changes in each ply.

(4) Predicting new laminate properties.

(5) Calculating the changed residual strength properties of the laminate.

The steps are repeated with increasing number of loads until failure is predicted. Various failure modes are also treated in the analysis. These include:

(1) Axial cracking in the load direction.

(2) Transverse cracking across the specimen.

(3) Cracking at an angle to the load axis along a fiber direction.

The failure modes are calculated by computing the laminate stress causing each mode of failure using a static fracture model. Failure stresses are compared, the lowest being the predicted laminate failure stress and represents the dominant mode of failure.

Fatigue failure occurs as a result of crack growth along preferred directions in the laminate as calculated by the static fracture model using unidirectional fatigue-degraded properties. An example of the capabilities of this model is illustrated in Figure 24. Residual strength curves for transverse crack propagation mode and axial crack propagation mode are plotted from calculations using the

static fracture model. The laminate's residual strength is determined by the lower of the two curves (solid line). This example shows the residual strength initially increasing, then decreasing until the strength equals the maximum cyclic stress at which point failure occurs.

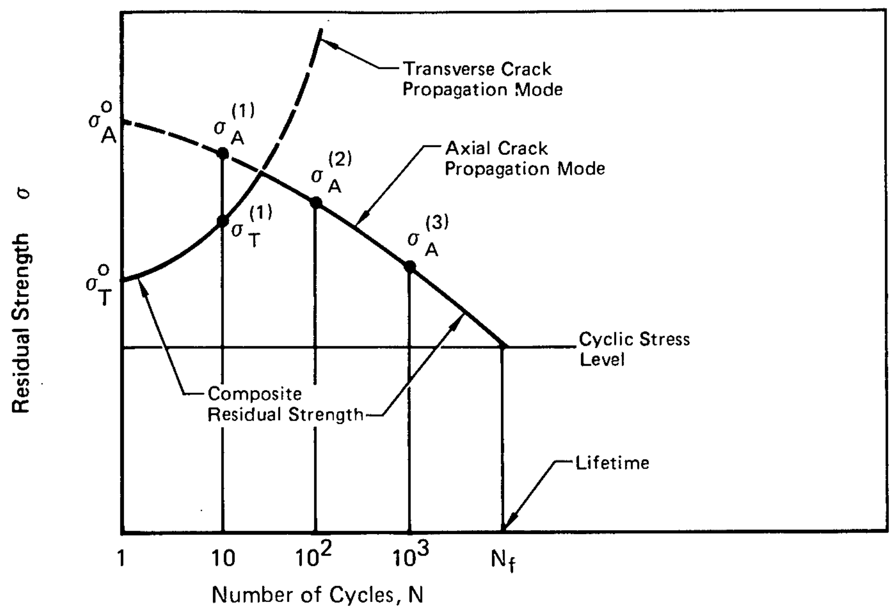

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FIGURE 24

MATERIAL DEGRADATION MODEL PREDICTS RESIDUAL STRENGTH INCREASES

This model is still under development. Additional capabilities have recently been added to the model by Ramkumar, et. al. (Reference 59). They have included interlaminar effects near the hole. Due to the lack of a statistically significant data base of unidirectional fatigue data, correlation has been inaccurate. Being based on fracture mechanics, compressive loadings have little meaning.

Utilizing unidirectional material fatigue properties to determine laminate residual strength and life is a desirable approach. This eliminates the need for extensive testing of numerous lay-ups and loading conditions. As

long as a static failure model can be accurately developed using unidirectional material properties, various configurations can be analyzed for fatigue.

The methods discussed above have basically taken a macromechanical point of view. Attempts have been made by other researchers (e.g. Reference 60) to approach the problem of composite fracture using micromechanical analysis. To date, these models have not been validated.

Current Research - Research on composite fatigue is continuing throughout the industry. Listed in Figure 25 are those major programs on composite fatigue which are in progress or will be initiated shortly. A brief outline of some current programs is given below.

Program	Sponsoring Agency	Performing Agency
In Progress		
Environmental Sensitivity of Advanced Composites	AFFDL	Grumman
Fatigue Spectrum Sensitivity Study for Advanced Composite Materials	AFFDL	Northrop
The Effect of Compressive Loading on the Fatigue Lifetime of Graphite/Epoxy Laminates	AFML	Lockheed
Residual Strength Degradation for Advanced Composites	AFFDL	Lockheed
Advanced Composite Serviceability Program	AFML	Rockwell
Design Spectrum Development and Guidelines Handbook	AFFDL	MCAIR
RFPs in Review		
Compression Fatigue Analysis of Fiber Composites	Navy	

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FIGURE 25
ON-GOING COMPOSITE FATIGUE PROGRAMS

Environmental Sensitivity of Advanced Composites (Reference 61) - The program objective is to define realistic environmental spectra and to develop methodology required to provide an alternative to real-time environmental test-

ing of composite structure. Tests combining fatigue cycling with environmental conditioning are being conducted.

Fatigue Spectrum Sensitivity Study for Advanced Composite Materials (Reference 62) - The objective of this program is to experimentally determine the sensitivity of various fatigue properties of composite materials and to develop procedures and guidelines for deriving realistic accelerated/truncated fatigue spectra. Specimens used in this program are two bolt bearing configurations.

The Effect of Compressive Loading on the Fatigue Lifetime of Graphite/Epoxy Laminates (Reference 63) - This program will experimentally and analytically ascertain the effect of compressive loading on the fatigue response of graphite/epoxy specimens with an unloaded hole.

Residual Strength Degradation for Advanced Composites (Reference 64) - Among the program objectives is to develop an analysis methodology to predict damage growth and residual strength of composite laminates subjected to fatigue loading. An experimental investigation will be conducted to verify the analysis.

Advanced Composite Serviceability Program (Reference 65) - The objective of this program is to develop a method, other than proof testing, to assure the safety and durability of advanced composite primary structure.

Design Spectrum Development and Guidelines Handbook (Reference 66) - The objective of this program is to systematically evaluate the effect of fighter wing load spectrum variations on the life behavior of composite structure.

These programs should contribute to the understanding of fatigue failure mechanisms. Information and analytical approaches developed in these contracts should be available for use in this contracted program prior to initiation of fatigue life activities in Tasks 4 and 5 (Figure 1).

SECTION IV
SELECTED METHODOLOGIES

The purpose of this section is to discuss analytical methods selected for static strength and fatigue life predictions for use in the remainder of this contract.

1. STATIC STRENGTH METHODOLOGY

Conventional methods discussed in Section III will be used to determine joint bolt-load distributions. For detailed analysis, the Bolted Joint Stress Field Model (BJSFM) has been selected as the static strength prediction method to be further developed in this program. This MCAIR developed model is a closed-form analytical method which can be utilized to predict laminate stress and strain distributions around an unloaded or loaded (bolt bearing) hole in an infinite orthotropic plate. This methodology has been incorporated into a computer program entitled "BJSFM". The program has the capability to handle material strength and stiffness anisotropy, general in-plane loadings (tension, compression, biaxiality, shear), multi-material (hybrid) laminates and arbitrary hole (bolt) sizes. It provides failure mode information using a ply-by-ply failure analysis routine. Complete stress and strain distributions are derived based on elastic analysis of an infinite orthotropic plate. Finite width corrections are incorporated. Only elemental testing of basic lamina (unidirectional ply) of a material system and one laminate configuration is required. Inelastic or non-linear behavior in the region immediately surrounding the fastener hole is accounted for. A final consideration in method selection was the utilization of existing material failure criteria. The BJSFM procedure has incorporated into its programmed logic several failure criteria. This will permit efficient study of failure criteria capabilities during test and theory correlation activities.

A comparison of BJSFM capabilities and those of other available methods is presented in Figure 26. It is recognized that the BJSFM procedure will require modification to

Variables/ Analytic Features	Model and Failure Analysis Capabilities				
	BJSFM 1	2	3	4	5
Geometry					
• Hole Size	√		√		
• Hole Spacing					√
• Width	√	√	√	√	√
• Edge Distance		√	√	√	√
• Thickness					√
• Countersinking					—
• Out-of-Roundness (Elliptical)	√				
Material					
• Othotropy (Lay-Up)	√	√	√	√	
• Stacking Sequence					
• Hybrid Lay-Up	√	√			
• Ineleastic Effects	√		√		
Loadings					
• Tension	√	√	√	√	√
• Compression	√	√			√
• Biaxial	√		√		
• Shear	√		√		
• Bearing					
– Single Axis	√	√	√	√	√
– Arbitrary Angle	√		√		
– Stress*	√	√	√	√	
– Displacement*		√			√
– Thickness Effects					√
• Thermal Loads					
Failure Criteria					
• Load Interaction	√	√		√	
• Non-Interactive	√			√	
• Fracture Toughness			√		
• Multiple Criteria Capability	√				
Solution Data					
• Stress/Strain Distributions	√	√		√	√
• Failure Initiation Point	√	√	6	√	
• Failure Mode	√	√	√	√	
• Failure Load	√	√	√	√	
• Critical Plies	√	√		√	
• Ply Stress/Strain	√	√		√	

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1 MCAIR bolted joint stress field model (reference 28)

2 Oplinger (reference 25)

3 Eisenmann (reference 27)

4 Waszczak & Cruse (reference 17)

5 Ojalvo (reference 13)

6 Fracture mechanics model - assumes 8 locations of failure

√ Model possesses capability

* Radial boundary condition

FIGURE 26
ANALYTIC MODEL EVALUATION FORM

include certain capabilities contained in other methods which are desirable. Current and planned capabilities of the BJSFM procedure are discussed in the following paragraphs.

BJSFM modular substructuring is illustrated in Figure 27 and permits revisions and updating changes to be made as required. Input data required are: lamina mechanical properties, in-plane loadings, hole geometry, and hole loadings. Output options permit data to be available after computation of each series of equations.

To obtain laminate stress and strain distributions due to combined bearing and bypass loads, the principle of superposition is used as shown in Figure 28. Fastener bearing is simulated using a radial stress boundary condition.

Whitney and Nuismer (Section III, 4) have postulated the concept that failure of a composite material with a stress concentration can be associated with point stresses or average stresses at or within a characteristic dimension from the edge of the stress concentration. The model generalizes the "characteristic dimension concept" to apply to failure analysis of orthotropic laminates under general biaxial loadings. This methodology has been incorporated into the BJSFM procedure.

Examples of analytic results obtained using BJSFM are presented in Figures 29 and 30. Circumferential stresses are plotted at the hole boundary for an unloaded hole and loaded hole configuration acted upon by uniaxial loadings. These analytic results illustrate effects of orthotropic stiffness (layup variations) and load direction on stress distributions, and location and magnitude of stress concentrations. Comparison is made with metal (isotropic) materials.

A correlation of test data and prediction for a laminate with countersunk fastener holes, loaded to failure uniaxially at various angles relative to the principal material

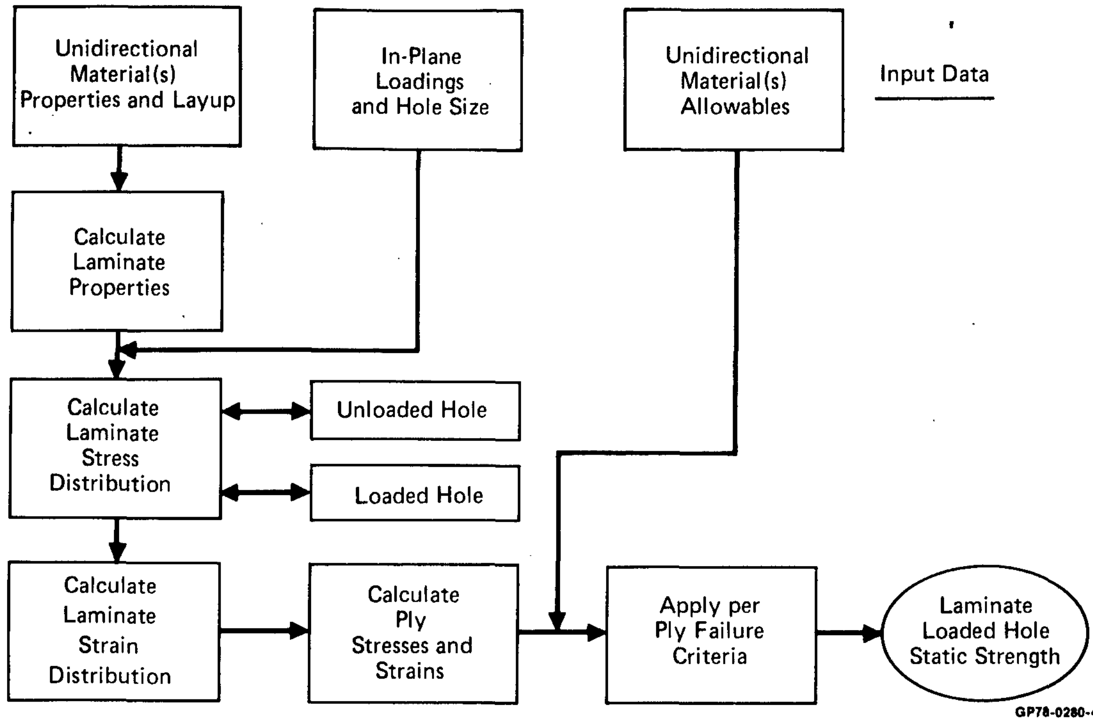


FIGURE 27
BOLTED JOINT STRESS FIELD MODEL - BJSFM
Computer Program Flow Chart

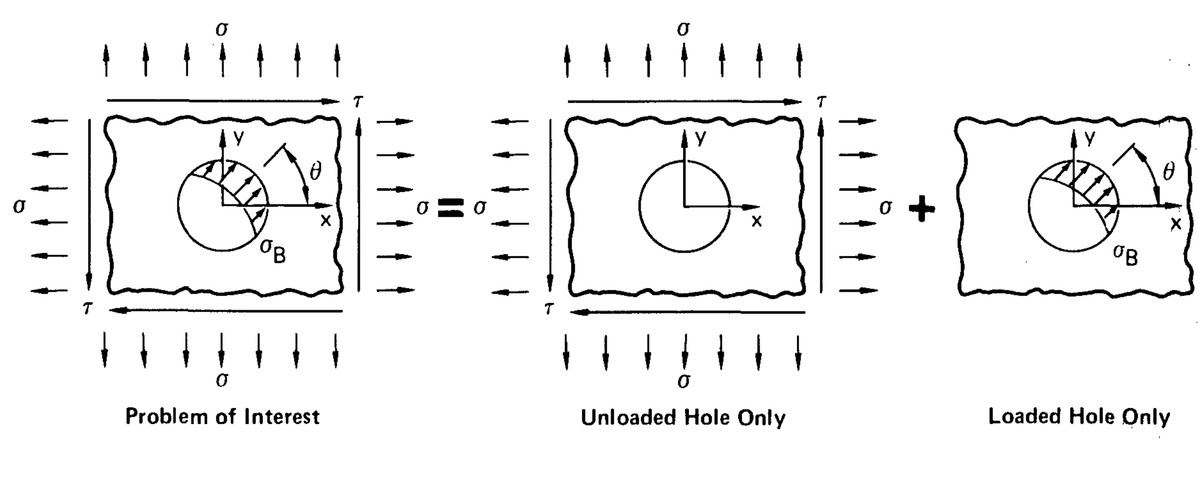


FIGURE 28
PRINCIPLE OF SUPERPOSITION USED TO OBTAIN ANALYTICAL SOLUTION

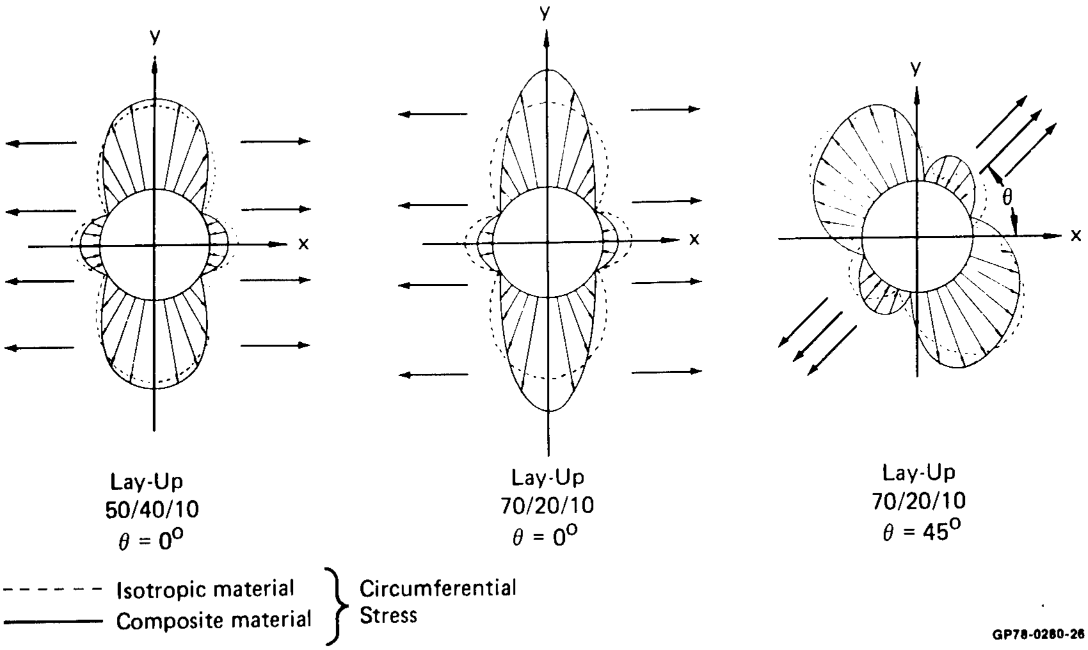


FIGURE 29
MATERIAL ANISOTROPY AFFECTS STRESS DISTRIBUTIONS

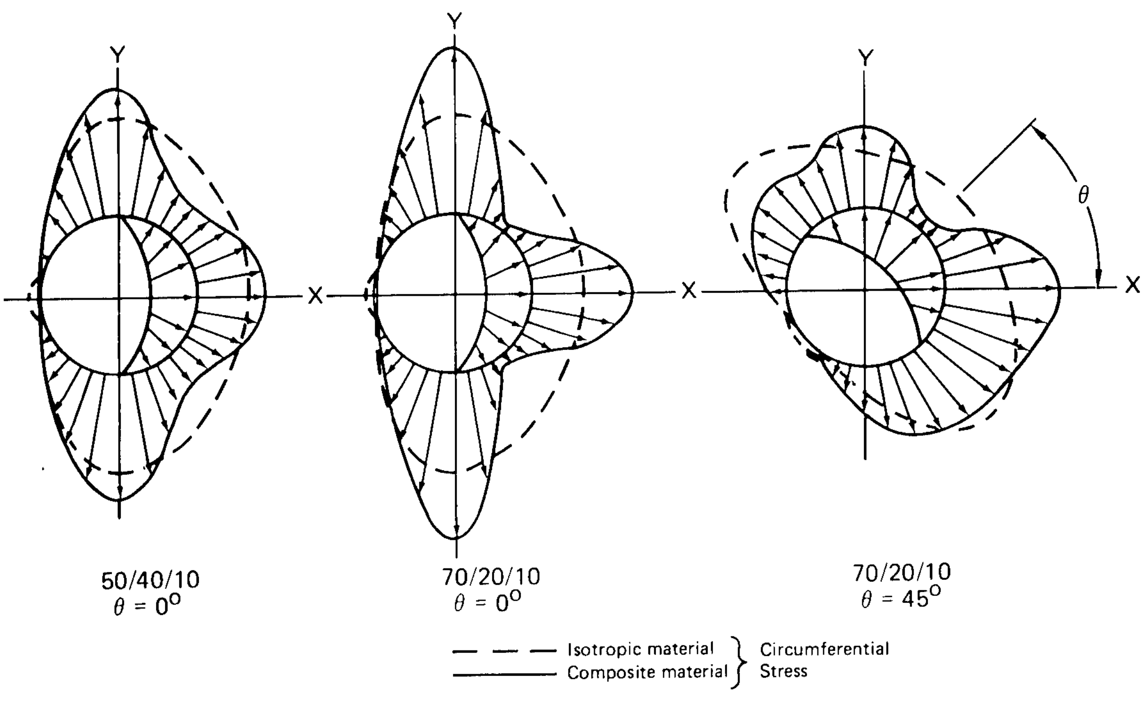


FIGURE 30
LOADED HOLE STRESS DISTRIBUTIONS ARE AFFECTED BY LAY-UP AND LOAD ORIENTATION

axis is presented in Figure 31. Correlation is excellent and shows that the procedures can account for countersunk fastener holes, strength anistropy, and biaxial loadings.

Good analytical correlation with hole size effects for various laminates loaded in tension is illustrated in Figure 32. Using lamina compression properties and allowables, hole size effects were predicted for laminates loaded in compression (Figure 33).

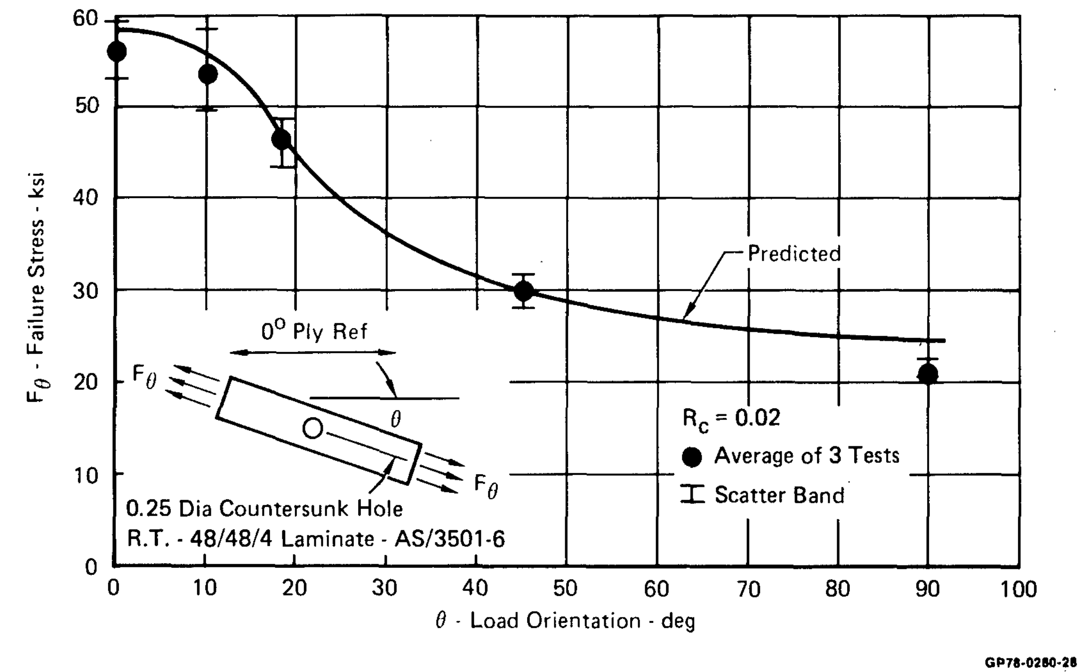


FIGURE 31
OFF-AXIS FAILURE STRESS IS ACCURATELY PREDICTED BY BJSFM

BJSFM utility was demonstrated by performing a parametric analysis to predict interactive effects of biaxial loads on laminates with unloaded fastener holes. Laminate strength, failure location and critical plies were predicted for a representative composite wing skin laminate as a function of biaxial load ratios utilizing the Tsai-Hill failure criteria in the BJSFM. Predicted failure stress and

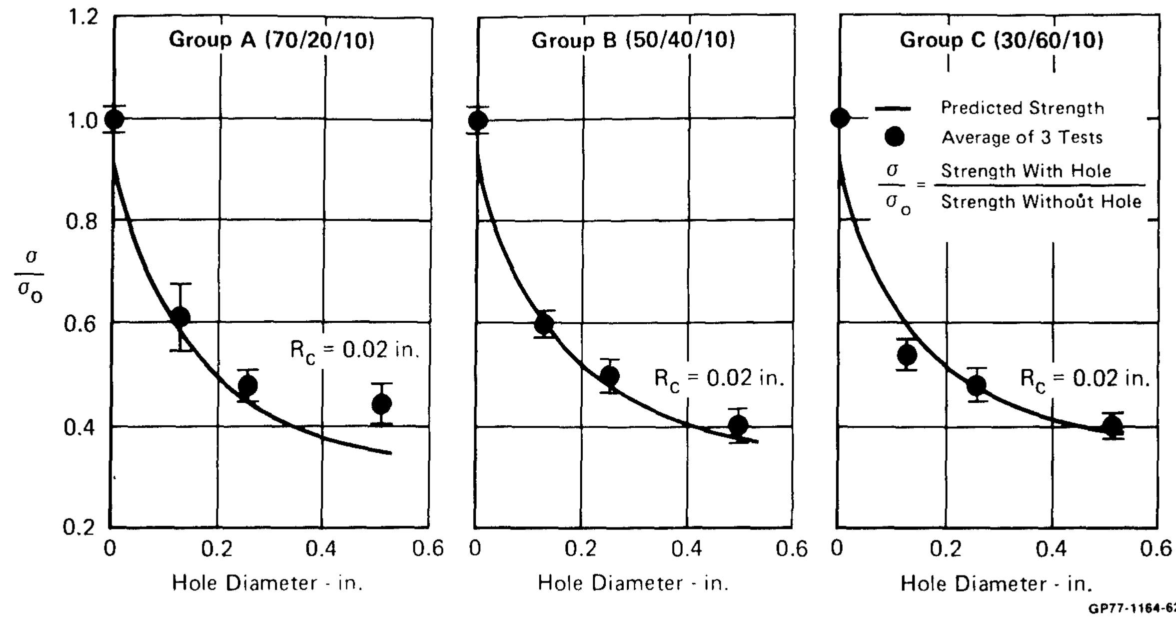


FIGURE 32
EFFECT OF HOLE SIZE AND LAY-UP ON LAMINATE TENSION STRENGTH

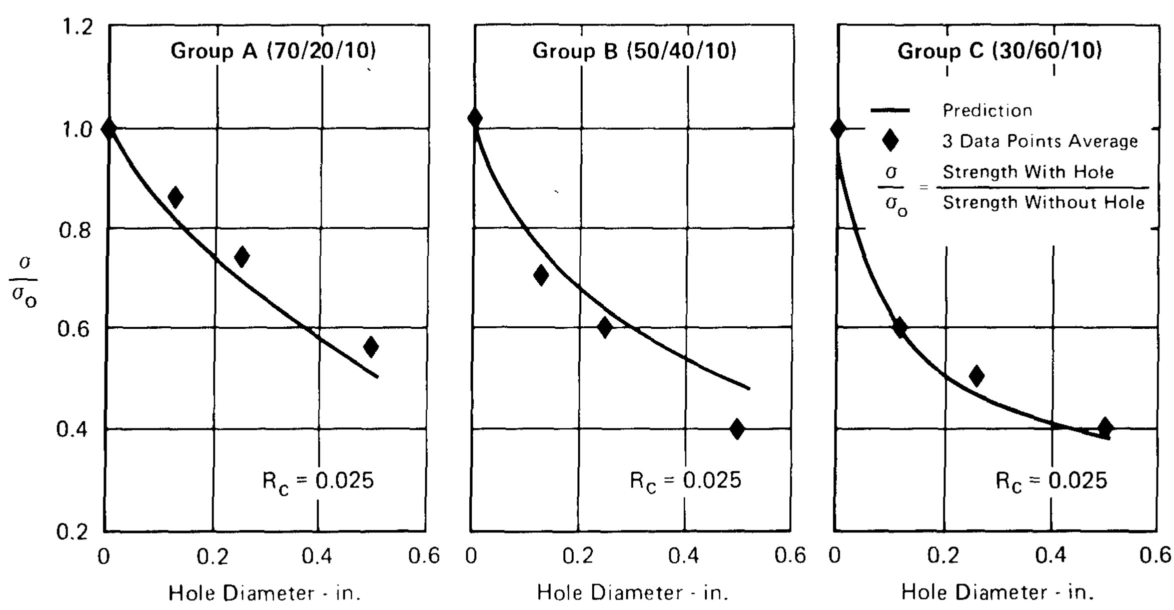


FIGURE 33
EFFECT OF HOLE SIZE AND LAY-UP ON LAMINATE COMPRESSION STRENGTH

changes in failure modes are presented in Figure 34. Predicted locations at the fastener hole boundary of first ply failure are presented in Figure 35. Predicted strain concentration factors for critical plies within the laminate are presented in Figure 36.

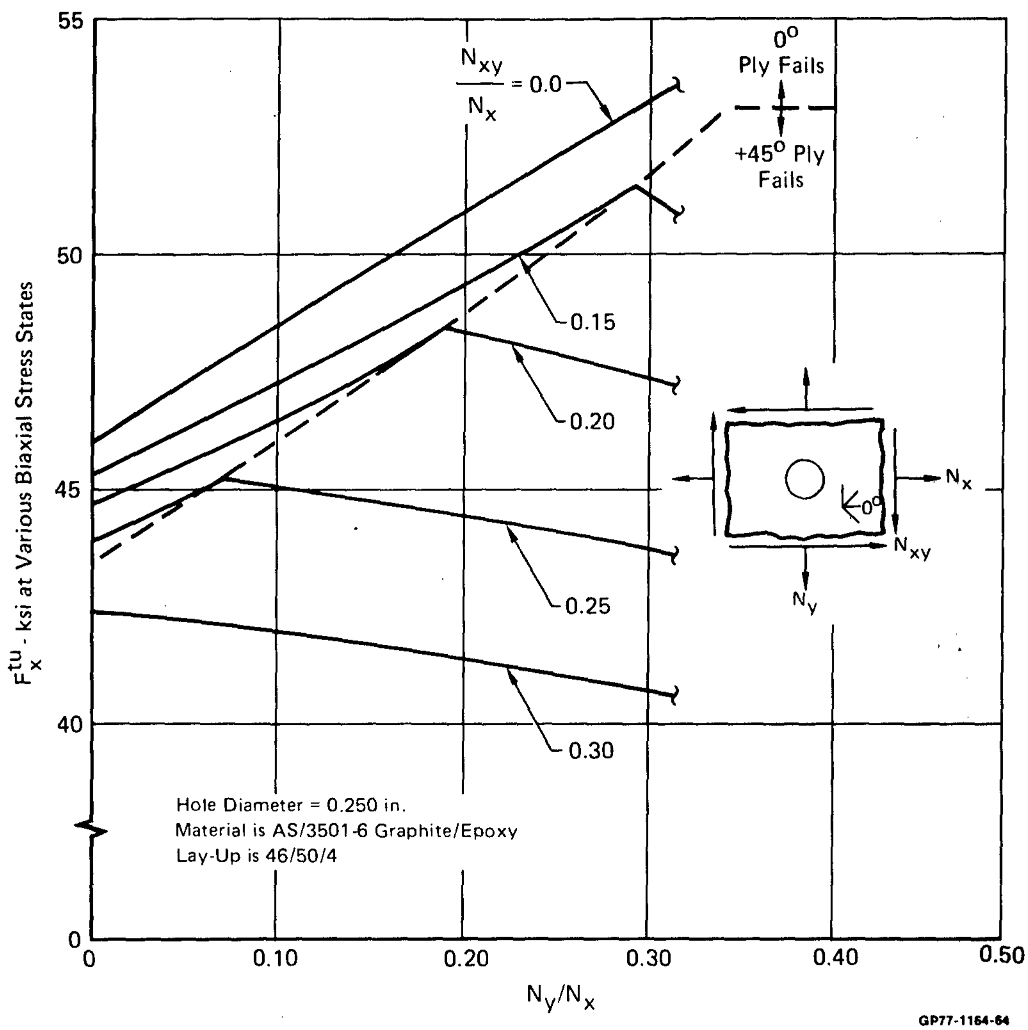


FIGURE 34
PREDICTED FAILURE STRESS DEPENDS ON BIAXIAL STRESS STATE

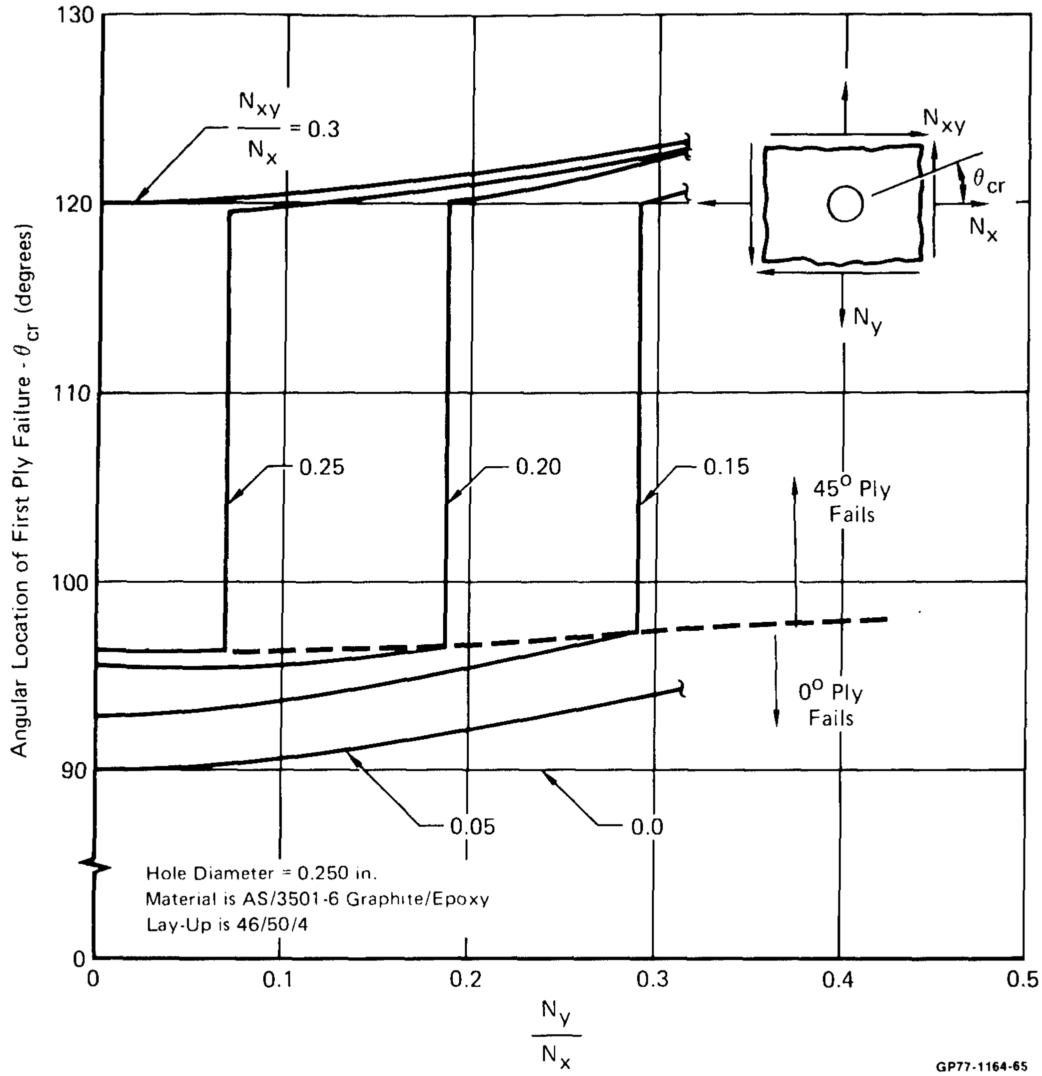


FIGURE 35
FAILURE LOCATION DEPENDS ON BIAXIAL STRESS STATE

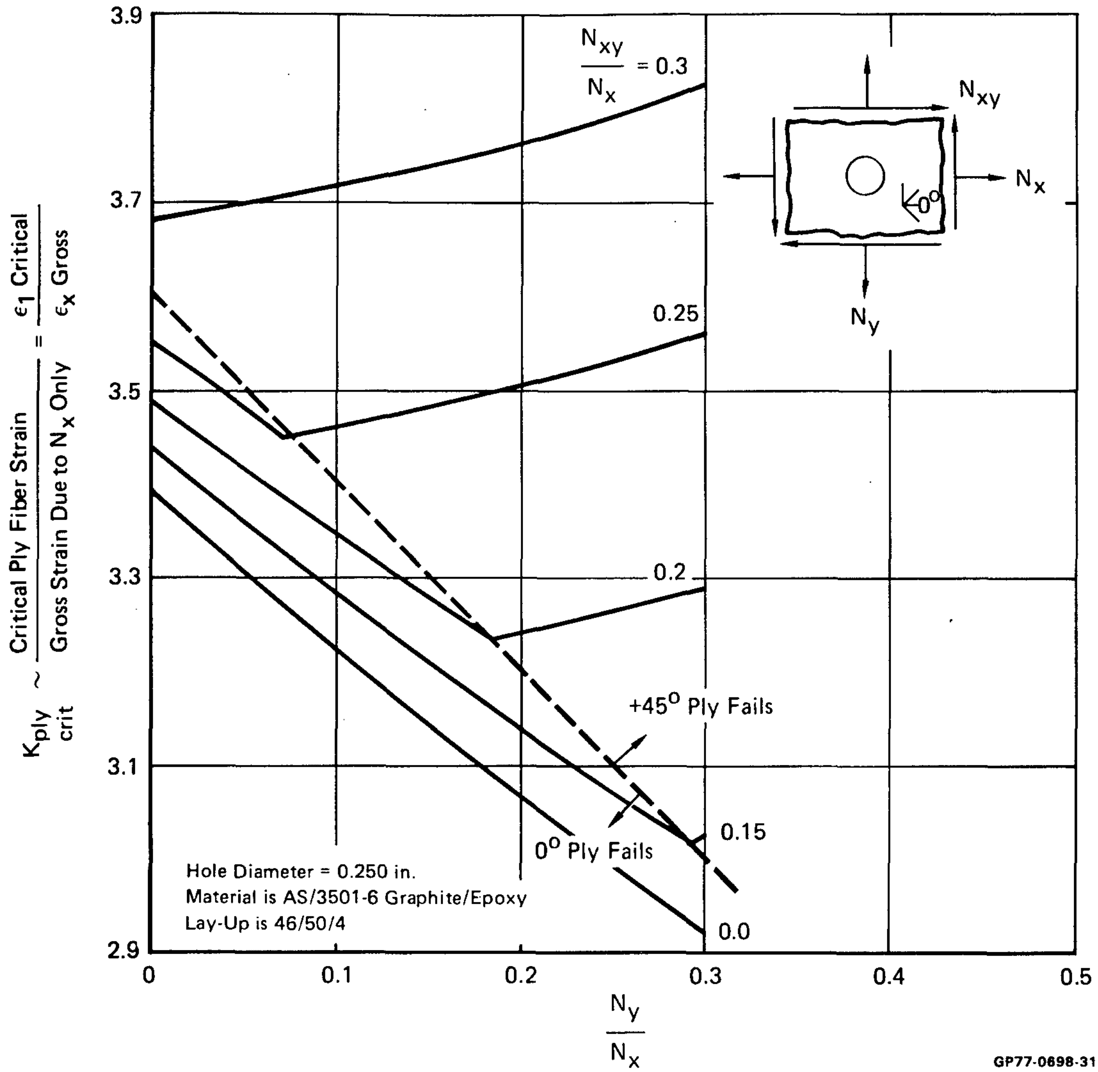


FIGURE 36
STRAIN CONCENTRATION FACTORS FOR CRITICAL PLIES REVEAL FAILURE MODE TRENDS

Finite width effects have a significant influence on the circumferential stress distribution around a loaded fastener hole. Utilizing a finite element model, width and edge effect curves were generated for various layups. An analytical procedure in BJSFM accurately predicts the stress field around a loaded hole in a finite width orthotropic plate. A comparison of finite and infinite plate solutions for the same layup show considerable differences. At a relatively large edge distance of 9 diameters and width of 8 diameters, stress distributions are corrected entirely by width correction factors (Figure 37). At edge distances of 3 diameters and width of 6 diameters, stress distributions are only partially corrected by finite width corrections (Figure 38). Thus, edge distance effects also perturb the stress distributions around a loaded hole.

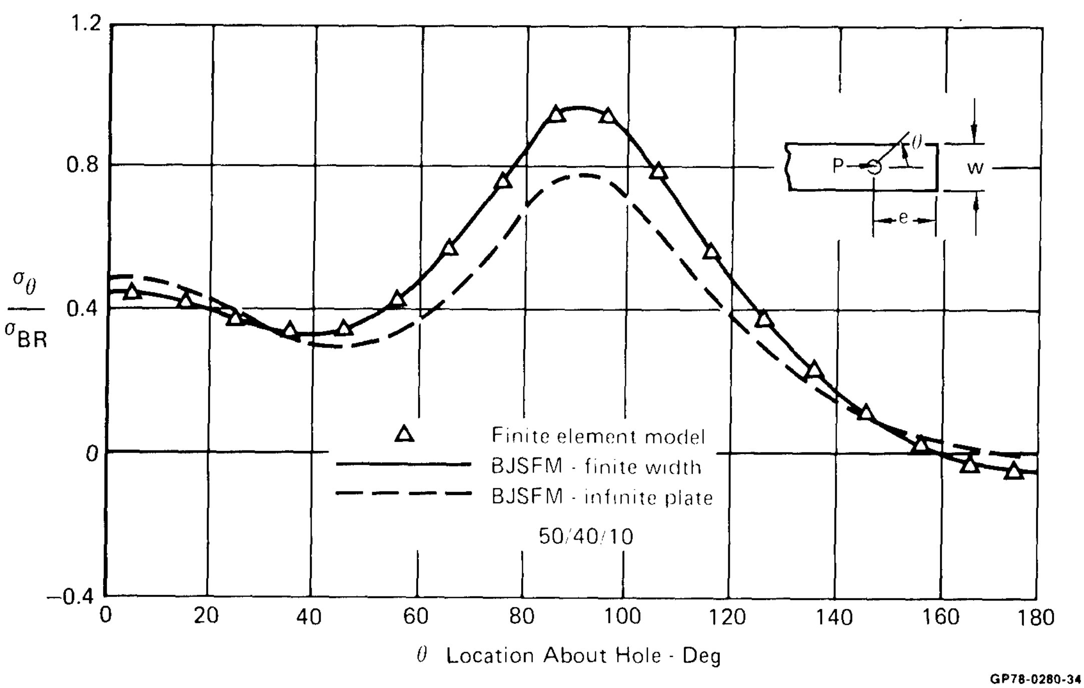


FIGURE 37
LOADED HOLE ANALYSIS CORRELATION
W/D = 8 e/D = 9

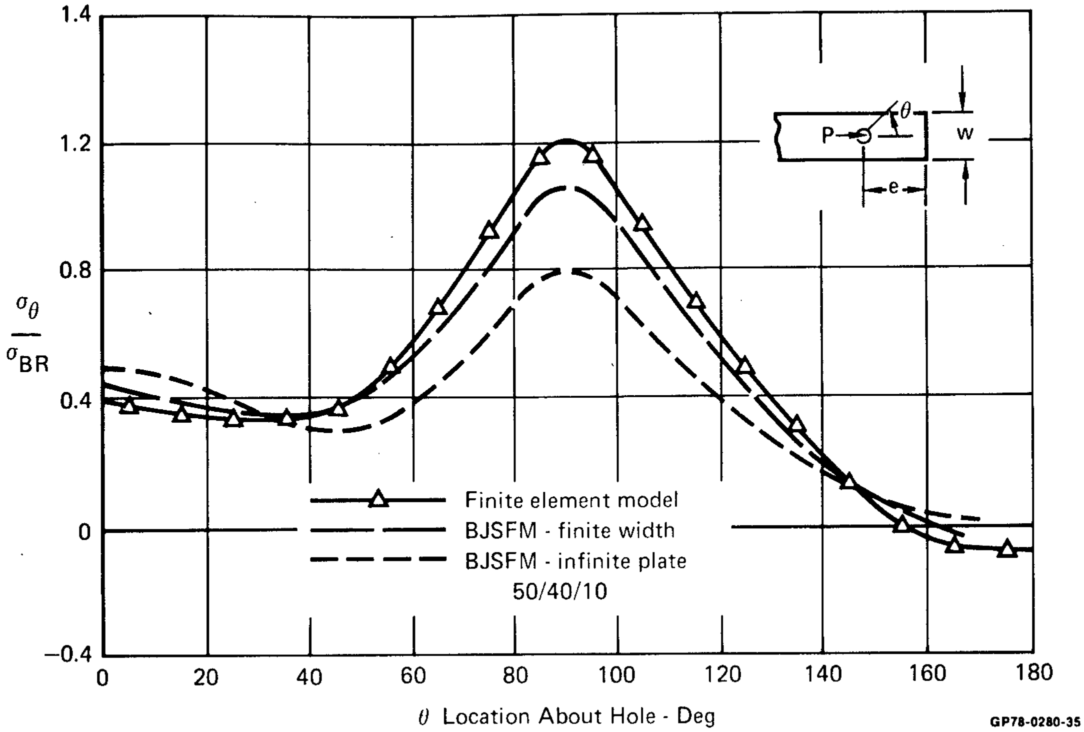


FIGURE 38
LOADED HOLE ANALYSIS CORRELATION
W/D = 6 e/D = 3

Currently, boundary collocation techniques are being investigated to fully account for all finite geometry effects. Future plans are to simulate radial displacement boundary conditions on the hole boundary and through iterative procedures address variation in stress distributions attributed to a changing fastener contact area. Previous work in this area by Opplinger and Cruse (References 18, 24, and 26) will be used as guidance in extending the capabilities of the BJSFM theoretical formulation.

2. FATIGUE LIFE PREDICTION METHODOLOGY

Current fatigue life prediction methods are empirical or theoretical in nature. Theoretical methods described in the literature require large data bases for statistical purposes or are not applicable to bolted joints. Therefore, other than an empirical approach, no fatigue life prediction

method is recommended at this time. Government funded research on composite fatigue is continuing (Figure 25). Information and analytical approaches developed in these contracts should be available prior to initiation of bolted composite joint fatigue life studies planned for Tasks 4 and 5 of this program (Figure 1). At that time, the best available fatigue life methodology will be selected.

SECTION V
CONCLUSIONS

An assessment has been made of previous and continuing work involving mechanically fastened joints in advanced composite structure. The state-of-the-art has been determined with respect to commonly used types of joints, common design practices, load distribution analysis, joint failure criteria, and fatigue life methodology. Methodologies have been selected for improvement in the remaining tasks of this Air Force funded program.

Aircraft ranging from lightweight fighter aircraft to the space shuttle use composite structural components which include mechanically fastened composite-to-composite or composite-to-metal mechanically fastened joints. With the exception of modifications to the composite constituent plies (e.g. inserts or softening strips), mechanical joints were found to be configured much like those seen in conventional metal structure. The F-18 lightweight fighter, AV-8B V/STOL, and B-1 bomber represent the latest state-of-the-art in production and research composite applications.

Bolted composite joint design practices with respect to edge distance and fastener spacing are not clearly defined among the aircraft companies. Minimum allowed edge distances and fastener spacings ranged respectively from 2-3 and 3-4 times fastener diameters. Most companies recognized a potential corrosion problem exists between graphite-epoxy and various metals (e.g. aluminum, cadmium plated steel). Generally, only tension head fasteners are used with composites and no interference fit holes, hole filling fasteners, or vibration driving are recommended. Torque values were found to be consistent with conventional metal structure guidelines.

Analysis of bolted composite joints in aircraft structural components follows similar directions throughout the industry. Analysis proceeds from overall structural analysis, to localized joint idealization and bolt-load distribution analysis, to assessment of strength through utilization of joint failure

analysis at individual fastener holes. Detailed stress analysis performed at individual fastener holes and associated application of failure criteria represent the primary area of needed research activity.

Theoretical and empirical methods are currently used to determine detailed stress distributions in the immediate vicinity of the fastener hole. State-of-the-art theoretical approaches include analytic, finite element, and strength of materials approximation methods. Analytic methods are preferred because of their potential generality, economy, and exactness. These methods are principally formulated from two-dimensional anisotropic elasticity theory.

Current joint failure analysis can be grouped into five classifications: (1) empirical, (2) elastic failure analysis, (3) inelastic failure analysis, (4) phenomenological failure analysis, and (5) fracture mechanics models. Physical variables considered relevant for accurate solutions were generally agreed upon throughout the industry. However, the degree to which variables were accounted for was different in particular methods. No single methodology accounted for all of the important variables (e.g. orthotropy, finite geometry, non-linear or inelastic material behavior).

In each classification of joint failure analysis, after detailed stress distributions are determined, strength is assessed by using material point stress failure criteria. No single material failure criterion is uniformly endorsed by any of the methodology originators. Direct studies regarding utilization of various material failure criteria for joint failure analysis are very limited. Only quadratic failure surfaces, which permit failure mode interaction, appear to be capable of being used to predict both bolted composite joint failure load and failure modes accurately.

Fatigue of bolted composite joints is currently accounted for through an iterative design-test procedure. Bolted composite joints generally have a high fatigue life; consequently most composite structural joints are designed for static strength

only. Fatigue analysis methodologies includes: (1) empirical correlations, (2) cumulative damage models, and (3) fracture mechanics models. Few methods have had extensive experimental verification. Research on composite fatigue is continuing throughout the industry.

Static strength and fatigue life analytic methods were assessed for further development under this contracted effort.

Static strength methodology was considered conventional with respect to methods used to determine joint bolt-load distributions and no further development seems warranted. However, for detailed stress analysis and static strength prediction in the localized region surrounding the fastener hole, continued research activity is required. The MCAIR developed Bolted Joint Stress Field Model (BJSFM) was selected for development. This closed-form methodology has the capability to handle material strength and stiffness anisotropy, general in-plane loadings, hybrid laminates, and arbitrary hole sizes. It provides failure mode information using a ply-by-ply failure analysis routine. Inelastic or non-linear behavior immediately surrounding the fastener hole is accounted for by using a "characteristic dimension" failure hypothesis. Only elemental testing of the basic lamina (unidirectional ply) of a material system and one laminate configuration is required.

Fatigue life prediction methodology currently are empirical or theoretical in nature. Current theoretical methods require large data bases. Government funded research on composite fatigue is continuing with most programs (reference Section III, 5) due for completion within the next two years. Therefore, in anticipation of new advances in analysis soon to be reported, no fatigue life prediction method is recommended at this time.

SECTION VI
RECOMMENDATIONS

The recommended objective for the remainder of this program is to develop improved analytic methods to predict strength and durability of bolted composite joints.

The proposed program is outlined graphically in Figure 39. In Task 1 - Literature Survey, completed and reported on in this report, commonly used joint designs were categorized, analytical methods discussed, and the Bolted Joint Stress Field Model (BJSFM) was selected as the basis upon which improved static strength analytic methods would be developed. In Tasks 2, 3, and 4, experimental programs will be performed to determine effects of joint design variables and manufacturing and service anomalies on joint strength, and effects of joint variables on service life. Task 5 will develop improved methods for static and fatigue life prediction based on previous experimental data.

The following sections will detail each of the tasks remaining in this program.

Task 2 - Evaluation of Joint Design Variables - The objective of Task 2 is to obtain baseline experimental strength data for graphite-epoxy to graphite-epoxy, graphite-epoxy to titanium, and graphite-epoxy to aluminum joints through an experimental test program coordinated with analyses. Task 1 analytic methods will be used to identify twelve most significant design variables for an experimental program. Planned interaction between theory and experiment in Task 2 is illustrated in Figure 40. The test program will verify prediction accuracy of methods of analysis used to evaluate the joint design variables. Testing will be performed at three environmental conditions. Baseline static tests will be conducted at room temperature, with and without moisture preconditioning. Tests will also be conducted at realistic elevated temperature and moisture contents representative of deployment profiles for multi-mission high-performance supersonic aircraft.

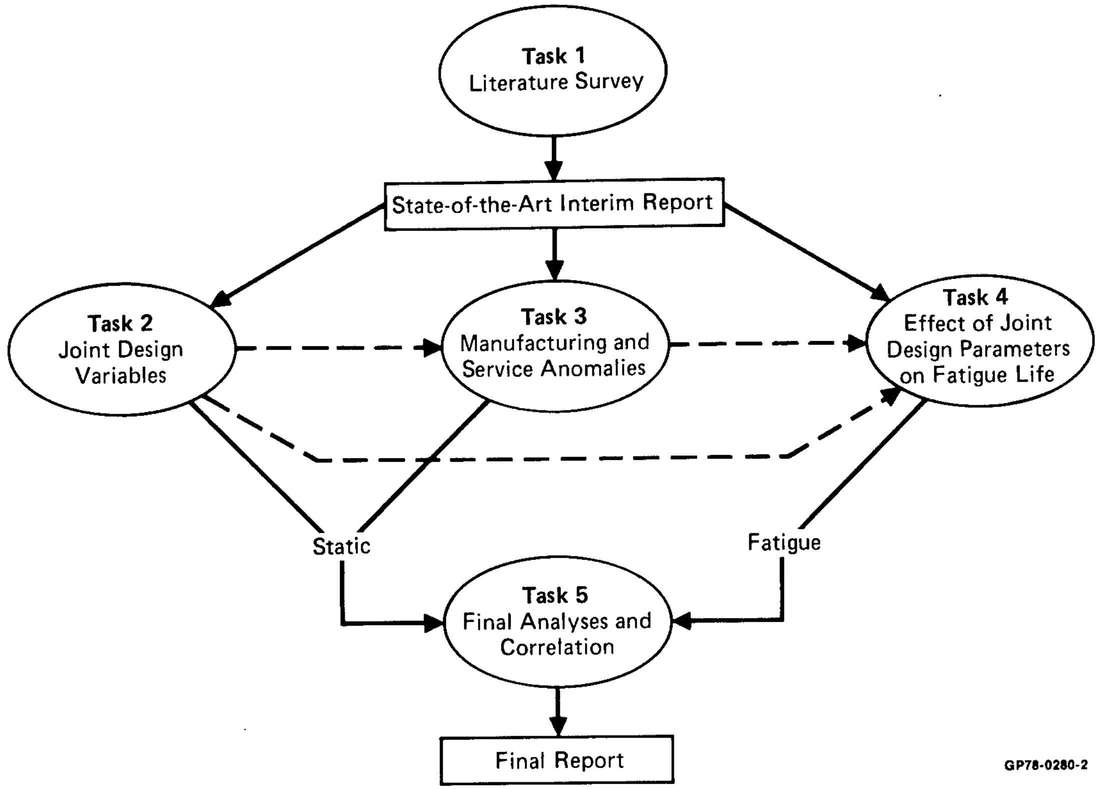
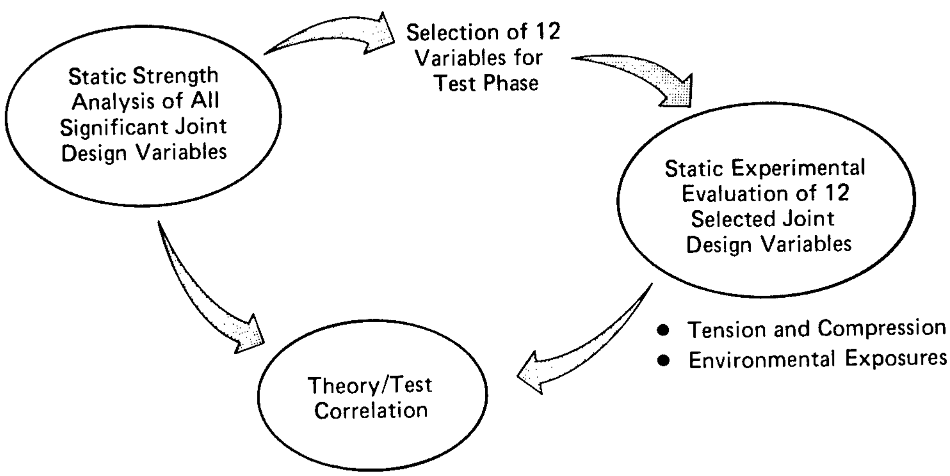


FIGURE 39
BOLTED COMPOSITE JOINTS PROGRAM



Objective: Obtain Baseline Strength Data Through an Experimental Program Coordinated with Analysis

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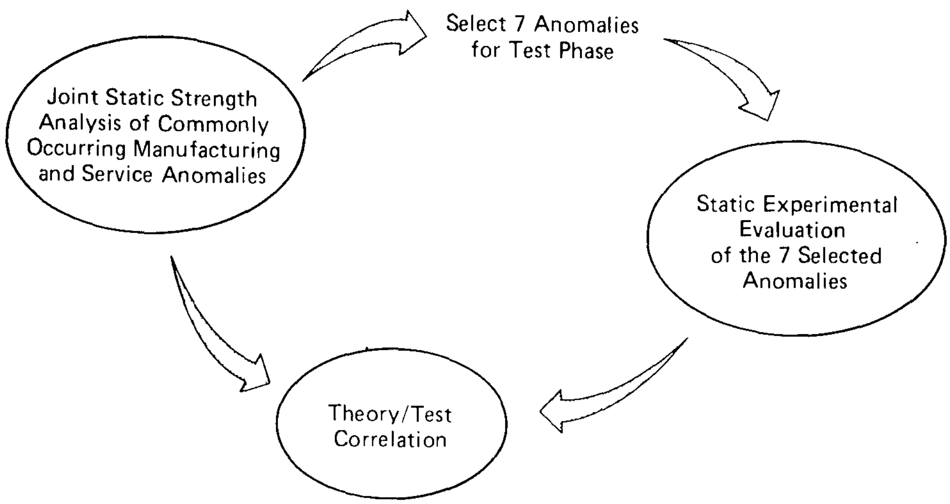
FIGURE 40
TASK 2 - EVALUATION OF JOINT DESIGN VARIABLES

Task 3 - Evaluation of Manufacturing and Service Anomalies - In this task, common manufacturing and service anomalies in bolted composite joints will be identified, their effects on joint static strength will be evaluated in an experimental program, and test data will be correlated with analytical predictions. Figure 41 highlights Task 3 activities. Seven bolted joint anomalies will be evaluated. Planned tests will provide experimental data on local strength reduction, and measurements of joint compliance to evaluate effects of each anomaly on joint flexibility.



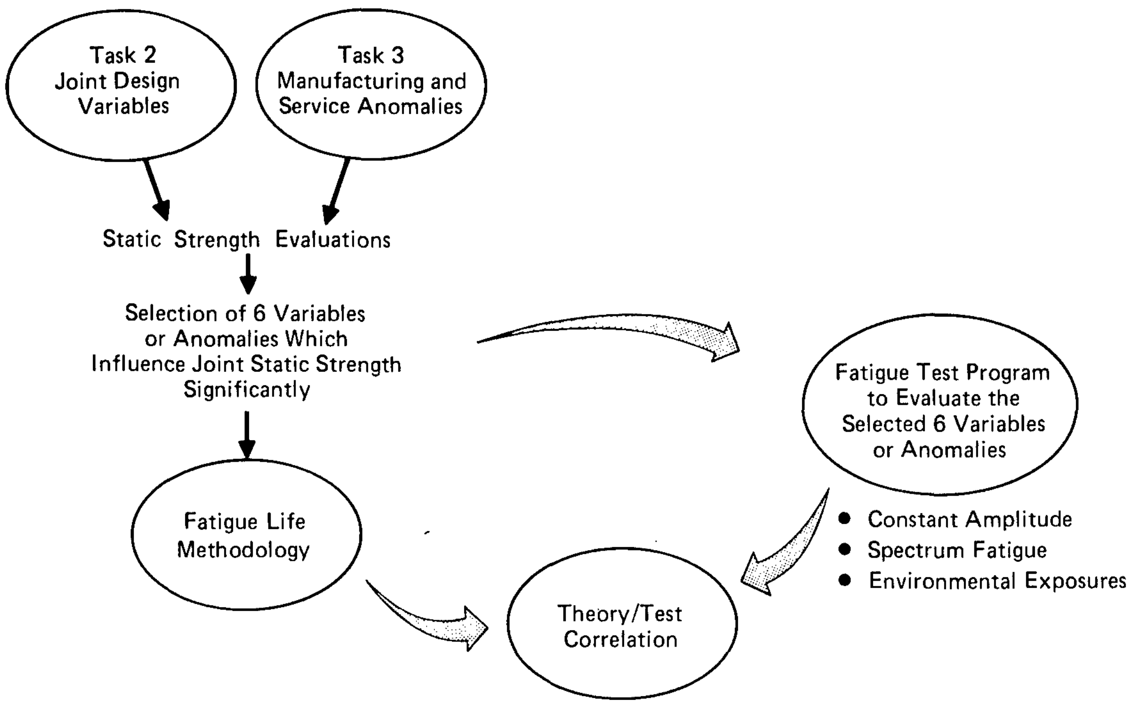
Objective: Identify Most Commonly Occurring Manufacturing and Service Anomalies in Bolted Composite Joints and Evaluate Their Effects on Joint Static Strength

GP78-0280-15

FIGURE 41
TASK 3 - EVALUATION OF MANUFACTURING AND SERVICE ANOMALIES

Task 4 - Evaluate the Effects of Critical Joint Parameters on Fatigue Life - The objective of Task 4 as presented in Figure 42, is to develop and implement a test plan which systematically evaluates the influence on fatigue life of the six design variables or manufacturing anomalies which have been

determined to have the greatest effect on static strength in Task 2 and Task 3. The final test plan will be tailored to provide data most directly usable in developing improved fatigue life methodology in Task 5. Specimen configurations developed and used to obtain static test data in Tasks 2 and 3 will also be used for fatigue tests to insure correlatable results.



Objective: **Systematically Evaluate the Influence on Fatigue Life of Design Variables or Manufacturing Anomalies Which Have Been Shown to Have Significant Joint Static Strength Effects**

GP78-0280-17

FIGURE 42
TASK 4 - EVALUATION OF CRITICAL JOINT DESIGN PARAMETERS ON FATIGUE LIFE

Task 5 - Development of Final Analyses and Correlation - Final procedures for predicting static and fatigue strength of bolted composite joints will be established using methods and data from Tasks 1, 2, 3, and 4. Desirable features of several methods will be combined into one improved approach if possible, as well as formulating new methods based upon observations of

specimen behavior and correlations of prediction with experimental data in Tasks 3 and 4. It is expected that a number of failure modes will have to be accounted for in joint failure analyses, and may require definition of different or combined failure criteria. Static and fatigue tests conducted in Tasks 2, 3, and 4 will be combined with existing data bases for composite structure. Using this data, developed analytic methods selected in Task 1 will be correlated to determine their predictive accuracy.

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